A New Technology for Designed and Controlled Filling of High Volume Quality Aluminium Castings

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Introduction

The manufacturing technology for cast heat exchangers has always been driven by the demands for new products, necessitating greater output and efficiency from smaller, lighter boilers of a complex shape, and this demand has pushed conventional foundry practice to the limit. Manufacturing heat exchangers is a strict task master for any foundry, requiring not only complete water integrity, but demanding the heat exchanger fins are produced to very close centres with a deep draw in order to produce the essential surface area for performance. These requirements result in the need for sand casts to be slimmer and the flow of molten metal into the mould to be more controllable as well as placing new demands on the moulding machinery and auxiliary processes such as core making. This paper concerns itself with the filling process and its influence over product capability and quality, especially as this part of the process lends itself to making the greatest step change in the manufacture of castings, and yet comparatively little is really known of how filling takes place and the limits of its control. Whenever step changes have taken place in product design, this has often resulted in the need to change the manufacturing method, which has resulted in three green field foundries being built by Baxi in the space of 25 years.

<table>
<thead>
<tr>
<th>Foundry 1</th>
<th>Foundry 2</th>
<th>Foundry 3</th>
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<tbody>
<tr>
<td></td>
<td>Wt of boiler = 128 lbs (58 kg)</td>
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<tr>
<td></td>
<td>No of pieces = 6</td>
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<tr>
<td></td>
<td>Output = 40,000 BTU*</td>
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<tr>
<td></td>
<td>Wt boiler = 75 lbs (34 kg)</td>
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<td>25 Years</td>
<td>No of pieces = 2</td>
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<td></td>
<td>Output = 50,000 BTU</td>
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<tr>
<td></td>
<td>Wt of boiler = 37 lbs (17 kg)</td>
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<td></td>
<td>No of pieces = 1</td>
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<td>Output = 60,000 BTU</td>
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With the introduction of the new environmental standards for domestic heating units, and the ongoing demand for products of distinction, it was recognised that current materials and manufacturing processes may not meet the demands of the future, and an assessment was required of limiting features and capabilities of our own and all current processes. This paper is a summary of that work and how findings and development work led to a new process that not only meets the Company's future requirements, but will meet the needs of all those seeking quality aluminium castings, in volume, at a low cost with new opportunities for the product designer.

* 1 BTU = 0.293 x 10⁻³ kWh = 1055J
Process Assessment

Current Position
This can be simply summarised by the following statement:-

What Does the Future Hold for our Core Technology of Heat Exchanger Manufacture?

Product
- Design Requirements
  - New environmental standards
  - High efficiency
  - Large surface area to size
  - Small – light
  - High thermal conductivity
  - High quality – 100% watertight
  - Resistant to condensation corrosion

Process
- Manufacturability – Existing Foundry
  - One process company – cast iron
  - Pushing frontiers in greensand moulding
  - Can stretch the existing process by the use of chemically bonded inserts
  - Still some mileage from developing runner systems and sand strength
  - Process capabilities fully developed in 3 to 5 years
  - Process known to limit some recent design requests

Material Investigation
It was thought that a number of products for the future would be operating at very high efficiencies or even in the condensing mode and in this case, the lower flue gas temperature produces a condensate that attacks traditional materials such as cast iron and copper when used in heat exchangers. Good thermal conductivity plays an important role in the design of the more advanced heat exchanger and was seen as a desirable feature. The reasons why it was decided to investigate the use of aluminium for heat exchangers is summarised below:

Why Aluminium?
- High efficiency produces low flue gas temperatures resulting in higher levels of corrosive condensate
  - Aluminium and stainless steel can resist corrosion
  - Copper and cast iron can not
- Thermal conductivity of:-
  - Aluminium = 100%
  - Grey iron = 25%
  - White iron = 14%
  - S/Steel = 9%
- Cheaper than stainless steel and can be readily cast
- Only a third of the weight of cast iron
- Ideally suited to greensand moulding and volume production
  - Freezing time for same modulus = to cast iron
- Reduces demands on mould properties
  - half the molten temperature
  - one third of the force on fill for equal velocity
Manufacturing Investigation

On examining a range of aluminium heat exchangers being produced in Europe, they fell into three main categories: assembly, welding and casting (see Fig. 1).

Assembly

Figure No 1 shows an assembly of three extruded tubes clamped between two cast manifolds. In reality, up to six tubes are used, which involves the use of twelve gaskets, which are not considered to be the most reliable form of water seal, when compared to a monobloc employing no gaskets. The end manifolds are usually cast, but have a wall thickness of generous dimensions to help with the porosity factor, and in some instances impregnation takes place. When asked why not cast a monobloc – the answers showed a lack of confidence in current casting processes to give the required designs at an acceptable price, with the assurance of a watertight product.

Welding

This was seen as a necessity rather than a desired process, to try and obtain the shape required. Access to welding areas was seen as limited designs, and the cost and difficulty of quality control were also quoted as disadvantages.

Castings

Although the casting process is ideally suited to the manufacture of heat exchangers due to its ability to form shapes ideally suited for the efficient transfer of heat from the combustion gases to the waterways, its use was restricted by process limitations and excessive manufacturing costs.

Die Casting

This had a limitation of how close the fins could be to each other, and the depth of draw. Stripping from dies could present difficulties and often the casting design had to accommodate the use of strip pins. Advanced heat exchangers are dependent upon a good design of the waterways and the limited use of cores placed constraints on some designs. The cost of the dies and their inflexibility to change was seen as negative factors, as was the slow production rate.

Core Assembly

Core assembly in chemically bonded material was not attractive due to the cost, the slow rate of production and environmental factors.

Gravity Sand

Gravity sand is limited in many instances by the moulding techniques and sand properties, as well as low volume production rates. Component design and properties is limited also by gravity filling.

A common problem to all the processes was the uncontrolled filling, using a metal that depends upon certain conditions being met during the filling process in order to produce reliable castings.
The Way Forward

The next step was to clearly define what was required to meet the specifications of the future and to provide that product differentiation essential to competitive excellence (in other words a Wish List) and to check that against what can currently be obtained. This is summarised below:

What is the Ideal Method for Manufacturing Aluminium Heat Exchangers?

- Wish list
  - High quality
  - Design flexibility of product
  - Allows complexity of shape
  - Low costs
  - Can produce in volume
  - Fast batch time
  - Fast low cost new product introduction

- Investigation
  - Study all current processes
  - Investigate new and developing processes
  - Talk to casting buyers to establish problem and degree of satisfaction with current suppliers

- Results
  - All current processes failed to meet the required criteria
  - New and developing processes – failed to meet requirements or a long way from market

  - Surprised by the level of dissatisfaction of buyers and product designers with current processes which they felt would cause problems related to the growth demands for aluminium

Having analysed the results of our investigation which covered a wide range of processes and many aspects both technical and commercial, it was concluded that the major factor limiting the manufacture of aluminium castings was the filling process, and if this could be resolved, and at the same time quality castings could be produced in volume at low cost, then there would be a process that would meet the need of industry in general, as well as the manufacturer of heat exchangers.
The Filling Process

As the majority of world aluminium castings are produced by gravity sand or die together with some pumped systems, this paper will concentrate on these forms of filling. The fundamentals of gravity filling are considered below:

Figure No 2 depicts a typical gravity system which by its very nature, shows how it is inclined to induce air into its system as well as being turbulent due to the lack of complete control during the whole of the filling cycle. Bubbles within the casting be they large or small, not only affect the porosity and subsequent strength of the casting, but also instigate cracks, during the bubble flotation through the molten metal, leaving behind an oxide film, which is often so thin that it cannot be detected. There is a tendency to under estimate the damage caused by bubbles. Also when carrying out x-ray or metallurgical analysis they are sometimes incorrectly confused with shrinkage defects.

Reference is made in Figure No 2 to a Reynolds No <2000 as this is a guide to the limit of bulk turbulence before the pattern changes to surface turbulence, for below a reading of 2000 viscous forces prevail, causing the flow to be smooth and laminar and approximately parallel to the walls, at higher values the flow becomes a turbulent, unpredictable melee of molten metal in motion, and this is the condition that so easily can appertain in a gravity system.

What is really important is the effect of this surface turbulence upon the quality and reliability of the casting. In the case of cast iron cast in greensand moulds, the oxide film is a liquid silicate and thus harmlessly separates and floats out, but in the case of aluminium, it is a different matter.

Figure No 3 shows how a splash of aluminium with formed oxide films, will overlap to form unwetted joins which become built-in cracks within the casting, some of which are so fine that they cannot be detected by normal foundry techniques. These folded oxide films build in unreliability within castings, so it is important to concentrate on understanding what conditions cause these film inclusions and what to do about it.

As referred to earlier, the boundary when bulk turbulence changes into surface turbulence occurs when the internal pressure exceeds the surface tension pressure, causing the oxide film to break up, dispersing it into the melt and hence the casing. This gives a more useful representation of what is happening during the filling process than the Reynolds Number in isolation and is represented by the Weber Number.

The Weber Number (We) is a ratio of inertial pressure $PV^2$ [$P =$ Density $V =$ Local Velocity] and surface tension pressure $2\gamma $ [$\gamma =$ surface tension, $r =$ radius of curvature of the surface]

$$We < 1 = \frac{V^2\gamma r}{2}$$

From the formula, a velocity can be derived which must not be exceeded if the natural oxide film is to remain intact

i.e. $V = \frac{2\gamma}{pr}$

Refer to Figure No 4 for a sketch and summary. Taking the surface tension $\gamma$ as approximately 1 Nm$^{-1}$, $p = 2.5 \times 10^3$, then depending on the value of $\gamma$, this critical velocity can be calculated. An unsupported droplet of aluminium on an unwetted surface stands approximately 12mm high, being retained in shape by the surface pressure of its skin. As this is a minimum skin effect, and the one that will be ruptured by the internal pressure, we can take "$r$" to be 6mm which gives a critical velocity of 0.37 m/sec. In the majority of castings, the wall thickness is less than the natural unsupport height of a droplet, so metal is now contained within the walls and the effect of surface tension comes into play. For practical purposes, for a wall thickness of 6mm ($r = 3$mm) then the critical velocity is 0.5m /sec. So for general
conditions filling velocities between 0.3 and 0.5 m/sec can be safely operated. In J Runyoro and J Campbell's paper "The Running & Gating of Light Alloys", a series of experiments are described where aluminium is discharged down a runner system with various size of nozzles to obtain a series of metal discharge rates at the ingate position. The metal discharges were filmed using high speed photography, which showed very clearly that when discharge velocities reached 0.5 m/sec, then the enclosing oxide skin became unstable and collapsed, and folding of oxide films could be seen to take place.

The question may be asked how important it is to keep the filling velocity below the critical velocity? This can be answered by referring to Figure 5, showing two graphs related to the filling velocity and subsequent strength of the material (published by the University of Birmingham). The top graph shows crack measurements that were recorded in 5mm and 10mm plates filled at various velocities up to 2.5 m/sec.

In the lower graph the bending stress of the plates, using a three roll technique is compared to the gate entry velocity. This graph shows very clearly that plates cast below the critical velocity have a bending strength which are 200 to 450% greater than those produced with gate entry velocities in excess of the critical velocity. The importance of this work is seen in the order of magnitude between the results, above and below the critical velocity. It is of interest to note that in the top graph it is sometimes difficult to detect any cracks in the plates when cast above the critical velocity, and yet they all fail at low bending strength which emphasises the point – you may not be able to see them, but they are there.

Gravity Filling

This system of filling is severely limited in terms of controlled filling for the following reasons:

At Some Point During the Filling Cycle the Critical Velocity will be Exceeded

The velocity of materials due to gravity = \( \sqrt{2gH} \)

\[ \therefore \text{height (H)} \quad = \quad \frac{\text{Vel}^2}{2g} \]

If the critical velocity is 0.5 m/sec then the height not to exceed this velocity in free fall

\[ = \quad 0.5^2 \quad = \quad 0.0127 \text{m} \quad (= \text{approx 13mm, see Fig. 6}) \]

\[ 2 \times 9.81 \]

In Figure No. 6 it can be seen that when the casting is filled from the bottom, the metal could rise 500mm in one second and we would still be within the critical velocity. In Figure No. 6 the start of metal filling from the top of the mould is shown, when in reality it has usually fallen much further from either a ladle or auto pouring unit. The subject of metal handling from ingot to actual filling the casting without incurring a mess of oxide films and entrapped bubbles will be referred to later, and is the subject of a future paper.

Gravity too Fast at the Start of Filling – Too Slow at the End – At the Very Best, A Compromise

This is the problem that has faced foundrymen from the beginning of time. The very nature of gravity filling is that at the start the effective head creating the velocity is high and as the casting fills, the filling velocity reduces considerably, dependent upon the height of the casting. (See Figure No 7 (a)). The high velocity at the start of filling can result in sand wash or metal penetration. Even with fairly sizeable ingates, velocities of 3 m/sec are not uncommon and the slim ingates favoured by many, result in even higher velocities. The forces
hitting the sand colds due to the flow of molten metal are all a function of the square of velocity \((V^2)\) which exaggerates the problem – see Figure No 7 (b). Approaching the end of filling there are two basic problems:

- Not only is the metal reducing in temperature as the mould fills, but velocity is reducing as well which affects the length the metal will run down a strip before freezing i.e.

\[
L_f = \text{Velocity (V) x Freezing Time (tf)} \\
L_f = V \times tf \\
tf = \text{KM}^2
\]

See Figure No. 7 (c)

Where \(K\) = A constant derived by experiment, in which the thermal conductivity of the mould plays a major part.

\(M\) = Section Modulus = volume divided by surface area. This is a sensitive condition when manufacturing heat exchangers, which by definition have a low section modulus.

- When trying to fill very narrow sections the metal experiences a back pressure due to surface tension and this can become large enough in certain sections to resist the diminished metallostatic pressure at the end of filling (See Figure No. 7 (d))

\[
P_{st} = \text{Back pressure resisting entry} \\
P_{st} = \gamma (1/R + 1/r)
\]

Where \(\gamma\) = surface tension (increases when cavity is less than natural droplet height)

\(R + r\) are the two orthogonal radii, which characterise the local shape of the surface.

**Can Runner Systems be Designed to Control a Gravity Fill During the Whole of the Filling Cycle?**

The simple answer to this is no, for the basic reason that the fixed dimensions of a runner system cannot cope with variations required in fill rate (kg/sec), with a velocity that changes in proportion to its gravity head. For example, a casting weighing 24 kg has to be filled in 8 seconds to ensure no short running at the top end of the casting, as the temperature, velocity and entry pressure reduce. Then conventionally it could be said that the average flow rate required is 24kg divided by 8 secs = 3 kg/sec. If the head at the start of the pour is assumed to be 0.65 metres and 0.15 metres at the end of pour, then the starting velocities, neglecting coefficient of discharge would be \((\sqrt{2} \times 9.81 \times 0.65) = 3.5 \text{ m/sec and 1.7 m/sec}\) respectively, this means for a fixed position in the runner system the quantity of metal passing would have to be 4 kg/sec at the start and 2 kg/sec at the end. If for reasons of casting shape it is required to fill slow at the start and fast at the end, then there is a real problem that cannot be overcome, even if the runner choke is over-designed and attempts are made at controlling the metal delivery rate from an autoupour or ladle.

With a fixed runner system, once the molten metal has passed the choke position and is on its way into the casting, it cannot be speeded up or slowed down within the casting in a controlled manner. It may be slowed down in an arbitrary manner by reducing the rate of metal flow into the runner, but it cannot be speeded up beyond the limits imposed by the choke.

**How Repeatable and Reliable are Gravity Fill Systems?**

A big failing with the design of many gravity runner systems, is that they do not take into account how metal is delivered to a runner system. What is the point of doing calculations and runner designs to try and fill a casting in a prescribed manner, when the quantity of metal being delivered to the system is totally different to that required. With the best will in the world, dispensing metal from a ladle is not accurate, even in the hands of the most skilled
operator, as changes in sprue position and adjustments to the ladle height as it empties, mean that no serious claims of controlled filling to critical velocity standards can be made. Automatic pouring units whilst being an improvement on ladle pouring, still fall short of the requirement for repeatable controlled filling to the standards being sought for the manufacture of prime quality and reliable castings every time. Figure No. 8 shows an autopour unit ready to fill a mould. The amount of metal released from the autopour in the first stages of the pour, is a function of the metal level in the launder and the nozzle diameter, assuming the stopper is raised sufficiently so that it does not restrict the flow. At the start of the pour the flow rate leaving the autopour is equal to:

\[ p \times \text{CSA} \times \text{Vel} \times \text{Cd} \]

where \( p \) = density,

\( \text{CSA} = \text{cross sectional area of the nozzle} \)

\( \text{Cd} = \text{coefficient of discharge} \)

\( [\text{Cd} = \text{coefficient of velocity} \ V_c \times \text{coefficient of area contraction} \ C_c] \).

Whilst certain guidelines are quoted in text books for the value of \( \text{Cd} \), related to various shapes and conditions, the only true value is one obtained by experimentation which the author has found to be necessary when working with cast iron. Conventionally the stopper is raised to its higher position at the start of pouring to give a fast metal fill of the down sprue and runner, then lowered at some point in the filling cycle to give a reduced flow. The point of lowering to the second position can be dictated by the following conditions:-

- Lowering the plunger to slow the metal down before it enters the casting. This is based on an optimistic assumption that all the calculations involved are correct and no variables are introduced, such as some mis-alignment of the autopour and the pouring cup of the mould. As nobody can see what is actually happening within the mould, the chances are that metal will arrive a fraction of a second too soon and sprays through the ingate into the mould. Experiments conducted at Baxi using an autopour filling a mould with cast iron by gravity, involved a system of electronic probes located in the area of the ingates in order to assess the time and velocity of arrival of the metal, produced a few surprises and a realisation of the difficulties we control, to any real degree of accuracy with such basic equipment.

- With a choke designed to give a higher than average fill rate at the start of filling the casting, a point will be reached when the velocity of the system is reduced, due to the effective head becoming less, and the system can no longer accept the rate of metal being delivered from the autopour. At this point the stopper is lowered to reduce the flow rate and prevent metal backing up and spilling all over the mould. The profile of fill rate produced by the autopour would be similar to that shown in Figure No. 8 (b). A theoretical fill profile of the system, not restricted by a two step flow rate from the autopour nozzle, is as shown in Figure No. 8 (a). The dotted line at the start of the fill in this diagram indicates the actual metal delivery from the autopour and shows the point in the casting where kinetic filling changes to pressure filling. Examination of figures 8 (a) and 8 (b) shows there is obviously some differences between what is expected to happen in theory and what is actually happening in practice, so there is a question as to which one does the foundryman design his runner system to?

- The third case would be when the system is highly choked, say at the bottom of the sprue, to give a long slow fill. In this case, the stopper would be lowered to its second position as soon as the down sprue and pouring cup had filled. It is interesting to consider the flow rate from the autopour in the throttled position. The nozzle is still the same diameter, the electrode is still the same height for metal level, so the only factor that has changed is \( \text{Cd} \) (coefficient of discharge) i.e. \( \text{kg/sec} = \rho = \text{CAS} \times \sqrt{2} \ \text{gH}, \times \text{Cd} \) (See Figure No. 8 (a))

It has already been stated that the \( \text{Cd} \) can only be obtained by experiment, so its value
cannot be calculated. It is therefore the responsibility of the autopour operator to adjust the second stage position as he starts pouring the moulds until he is satisfied with the results. This practice can vary from operator to operator, and how often are the times for the two stages checked back against any initial calculation for the runner system?

From the comments made in this section of the paper, the importance of matching the delivery from the autopour with the runner system design can be appreciated. As pattern changes take place, so the runner system demands change and it would be ideal to change the diameter of the autopour nozzle accordingly, but unless one is willing to suffer some significant down time, this has to wait until the end of the shift. What happens, therefore, in reality is that a compromise solution rather than an optimum choice is accepted.

Another major problem with the repeatability and accuracy when filling by gravity is the alignment of the pouring unit with the runner system. Referring to Figure No. 8 and considering the velocity of the metal arriving at the base of the sprue (which is a popular place to position the system choke), it can be seen that the velocity head is \( H_1 + H_2 + H_3 \).

Therefore, with complete alignment the velocity at the base of the sprue is equal to: \( \sqrt{2g (H_1 + H_2 + H_3)} (C_d, C_d', C_d'' , C_d'') \) or "X". If the autopour and the mould are misaligned, then the metal may hit the side of the pouring cup and become turbulent (see Figure No. 9) in which case an approximation can be made giving the velocity at the base of the sprue as \( 2gH_1 (C_d, C_d') = "Y" \).

To design the cross-sectional area at the base of the aprue, the following formula can be used:

\[
p \times \text{Velocity } "X"
\]

where \( p/\text{sec} \) is what is being delivered by the autopour and the velocity is when all the pouring system is in alignment.

At the end of pouring the casting, the filling velocity has changed and the coefficient of discharge is very different as it now has to account for the trial system of runner, ingates and casting. So the ideal CSA at the base of the sprue at the end of pouring is equal to:

\[
p \times 2g (H_1 + H_2 + H_3 - H_2 \times C_d \text{ system})
\]

which will inevitably be a different value to the value at the start of pouring – so which value should be taken? In most cases, it will be the higher value, which indicates that the pouring conditions can never be ideal during the full filling cycle and at some point there will be a tendency to introduce air into the melt stream.

What About Horizontally Made Moulds, are They Better Suited to Gravity Filling?

This is not really a question of being better than vertical made moulds, it is more the case of exchanging one set of problems for another. Obviously the flow of metal into the casting is dependent to a large extent upon the actual design of the runner, and especially the sizing and positioning of the choke area. However, there are some general concepts that are worth considering:-

- In the horizontal mode, once the metal has passed the control point in the runner system and enters the casting, it can virtually wander at will, being influenced only by the cross sectional area of casting, slopes or actual drops. Trials in the filling of plates have shown that it is a very random affair, and repetitive filling exercises never produce exactly the same pattern of filling. Filling vertically against gravity does give some degree of control and if ingated correctly the inrush can be reduced and as the casting starts to fill, it becomes settled and its filling pattern can be predicted with some degree of confidence.
- Most horizontal systems have some limitation on the head pressure available in the cope half of the mould, which restricts the use of fine finned work requiring some head to overcome back pressure. The limitations of head pressure can reduce also the required velocity necessary to ensure that adequate freezing lengths \( (L_f = V_c \times t_p) \) are available for thin sections, especially in the cope half.

- It is usually necessary to place the runner on the joint line, which would cause 'waterfall' in the drag half which is against the principle of filling that is required to be promoted (See Figure No. 11 (b)).

A paper by A. Nieswamay and H. J. J. Dean entitled "Experiments on Mould Flow in Thin Wall Castings" was found to be of interest during the investigation phase of the project, especially as it related to thin sections cast in the horizontal mode. Figure No. 10 shows the arrangement of their experiment, in which horizontal plates were cast, with the top half being a glass plate, through which the filling sequence could be recorded by a high speed video camera. The thickness of the plate was set at various heights ranging from 18mm down to 4mm. One of the objectives was to see the effect of reducing the plate thickness below the natural droplet height of 11 mm. Figure No. 10 (b) shows the pattern of filling as observed in the plan view, for an 8 mm plate. This experiment is very interesting as it shows the aluminium hitting the far wall from the ingate, dividing into different streams up the side walls and freezing as later metal flowing from the main stream from the ingate folds over the solidified sections. So, there is a filling operation with critical velocities well below those for bursting the oxide film, but causing a faulty casting by allowing the oxide bearing streams to split and come together at different times of the solidification cycle, causing excessive cold lapping of the casting.

In the conclusion of this paper, reference is made to the fact that, especially below the 12 mm droplet height, the liquid metal escaping the ingate is crushed, giving an unpredictable way of mould filling in separate streams, and in the case of the thinner sections, local freezing in the separated stream caused voids to appear in the casting.

There are some casting shapes that do lend themselves to casting horizontally — such as wheels or discs as they can be ingated from the centre, or around the periphery so that the metal flows to a number of points at the same time in a manner that is conducive to horizontal flow (see Figure No. 11 (a)). Sometimes when wheels or discs are cast in the vertical phase with slow ingating and very little effective head at the end of the pour, the rate of filling drops off rather quickly from the start to the end of the pour, giving a wide temperature differential from bottom to top of the casting. In extreme cases the metal may fail to reach the top of the casting in a sufficiently liquid form to give a sound structure, and this results in the infamous 12 O'clock defect (see Figure No. 11 (c)). With a pumped system a disc or wheel cast in the vertical phase would not suffer from the same problem, for once the metal has passed through the ingate, it can be filled in a fast uniform manner, allowing little time for temperature differentials to occur, and ensuring that the 12 O'clock defect is eliminated, together with oxide films damage (Figure No. 11 (d)).

**The Way Forward – Controlled Pumping**

Having examined gravity systems in detail, it was realised that they could never provide the controlled filling which is required and would always place limits on quality and complexity of design. The answer must be to use a pump filling against gravity. The advantages of using a pump are seen to be as follows:

- Provided the controls are sensitive enough, a casting can be filled exactly how required. If a slow rate is required through the ingates, it can be so. If the top half of the casting requires a high rate of filling and an increasing pressure then this requirement can also be met.
• One of the first rules of reliability is repeatability and using a computerised fill programme it can be ensured that every casting is filled exactly as required every time.

• Not having to use pouring cups and down sprues, a significant saving due to improved mould utilisation can be obtained.

• Whilst still controlling the critical velocity of filling, the casting cycle can be matched to the fastest mould making operation.

The Wish List Answered – The Alchemy Process

The use of a highly controlled electromagnetic pump filling against gravity with scientifically designed runner systems, provides an answer to the first half of the "Wish List", which is summarised below:-

Alchemy Process Concepts Filling Process In-Line with the Law of Physics

• Controlled filling velocity does not exceed oxide film strength or introduce air bubbles

• Filling is in the vertical plane – giving directional control

• Result – High integrity castings that are:
  – Aerospace quality
  – Pressure tight
  – Thin wall – lower weight
  – Can be welded
  – Can be heat treated
  – Suitable for finishing process temperature equal to and greater than 250°C
  – Do not require impregnation

To achieve all the manufacturing advantages sought, the second half of the "Wish List" would require combining the pump technology, with the technology of high speed greensand moulding. Working with Professor John Campbell who had agreed to take the Baxi Chair of Cast Metals Technology at Birmingham University, it was possible to combine his expertise in aluminium and pumped systems, with Baxis own expertise in greensand moulding using a Disa 2130 moulding machine within our purpose built green field foundry. The process elements are shown in Figure No. 12 and its attributes are summarised below:-

Process Attributes

• The process is "Unique" in being able to satisfy all the customer requirements of:
  – High quality
  – Low cost
  – High speed – high volume
  – Complexity of shape – design freedom
  – Fast batch changing
  – Low cost and fast new product introduction
  – Ideally suited for complex work

• It has been designed and developed to meet the growth market for aluminium castings
Greensand

The choice of using greensand for the moulds was not automatic, as consideration was given to chemically bonded materials, and to the use of zircon sand. Tests were conducted using different modulus sections formed in greensand, and the time of freezing was established to prove the suitability of silica sand when casting thin sections. It is of interest that even down to a very low modulus values, both cast iron and aluminium had the same time of freezing.

Why Use Greensand as the Moulding Media?

- Advanced greensand technology is available at Baxi which provides distinct advantages over conventional plants
- Disa flaskless moulds – highest output – no problems with boxes
- Superior vacuum system for filling and compaction
- High developed sand strength – tensile and wet tensile
- High mould hardness – good surface finish
- Refractory nature of green silica sand provides good fluidity – compared to other moulding materials
  - The Alchemy Process – wall thickness down to 2 mm.
  - Using zircon sand – wall thickness limited to 4mm
- No environmental problems – compared to other processes using chemically bonded sands

Cores

Often during the course of the investigation, it was found that the processes used had difficulty in manufacturing castings which required the use of complex and delicate cores. In fact, some processes could not produce cored components such as a mono block heat exchanger. Thoughts on cored work are listed below:

The Use of Cores – Design Opportunities

Any casting process can only reach its full potential if cores can be used easily and effectively

Alchemy

- In the Alchemy Process cores can be placed fast and accurately with the Disa Combisetter all within the 10 sec cycle time of the machine
- Some give for locking core prints – ideal for holding – no breakages
- Core sand returned to moulding sand – no cleaning problem
- Cores retained in refractory sand for the length of the moulding line providing ideal conditions for core breakdown
- Ideal for producing monobloc castings
Manufacturing Advantages

Let us now examine some of these manufacturing advantages in detail:-

**Volume**

There is no doubt that Disamatic moulding with its ability to operate at high volumes is an attractive proposition for supplying aluminium castings to the Automotive Industry, especially when they make the link to the high quality provided by controlled pump filling. A summary of comparative rates of production for various processes is shown below:-

<table>
<thead>
<tr>
<th>Process</th>
<th>Production Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cycles per hour</td>
</tr>
<tr>
<td>Disamatic sand moulding</td>
<td>200 - 360</td>
</tr>
<tr>
<td>Sand casting – automated box</td>
<td>100 - 200</td>
</tr>
<tr>
<td>Squeeze casting (liquid)</td>
<td>42 - 90</td>
</tr>
<tr>
<td>Squeeze casting (semi solid)</td>
<td>42 - 90</td>
</tr>
<tr>
<td>High pressure die casting</td>
<td>25 - 35</td>
</tr>
<tr>
<td>Gravity die casting</td>
<td>10 - 20</td>
</tr>
<tr>
<td>Low pressure die casting</td>
<td>8 - 15</td>
</tr>
<tr>
<td>Forging</td>
<td>NA</td>
</tr>
</tbody>
</table>

One of the first questions which is asked about the process, is "How can you produce at these speeds, when you have to wait for the metal to freeze before disconnecting the pump" The answer is that it is not necessary to wait for any metal to freeze, for as soon as the pump has filled the mould, a very cheap shut off device operates at the mould and pump nozzle interface fully sealing the mould and allowing the mould to index and the next cycle to start. Production rates of a 10 second manufacturing cycle are readily demonstrated on our pilot plant, whilst still maintaining critical filling velocities. As a comparative exercise with gravity die casting, the implications were examined of manufacturing a 5 kg heat exchanger by both processes and the production rate summary is shown below:-

**High Volume – Cycle Time Independent of Metal Freezing Time**

- Cycle time for Alchemy process – 10 to 12 seconds compared to die times of 4 mins to 14 mins
- Disa mould size larger in area than most gravity and production type low pressure machines
- The greater the casting weight (within reason) the greater the advantage of the Alchemy process
  - Does not have to wait for metal to freeze
  - Larger mould as compared to most die machines
    - Increases the range of product opportunity
- Compare the output of a standard gravity die machine of 15 castings per hour (5 kg) to the Alchemy plant of 1,800 castings per hour (5 kg)

This comparison is shown in Figure No. 13. One of the interesting elements brought to light in this comparison is that in order to match the production rate of one Disa, it would be necessary to purchase 120 single station die casting machines, which answers a question often raised about the comparative capital costs of both processes.
**Tooling**

When carrying out the exercise into the real cost of cost of castings produced by the various competitive processes, the cost of tooling was identified as a major element which for commercial reasons was mainly excluded from the price of the casting. Often the tooling was owned by the casting buyer, who then had the freedom to move his orders from foundry to foundry in search of the best value. To obtain the real cost of the casting, the tooling cost should be added to the manufacturing cost of the casting. The cost could be shared over the life of the tooling, or the length of the contract whichever is the most realistic solution. When considering the tooling cost, an allowance should be made for maintenance as well as the initial purchase price. Some of the factors, when considering differences between the cost of dies against patterns for greensand moulding, are listed below:

**Comparison of Die ~ Pattern Costs**

- In the Alchemy Process the patterns do not come into contact with the molten metal
  - Pattern life up to 1,000,000 cycles
- In die casting the dies face the molten metal
  - Die life up to 80,000 cycles
- Patterns for the Alchemy Process are relatively simple and can usually stand some design changes
- Dies are more complex and require temperature probes and cooling ducts
  - They cost more and are not easily modified
- From previous example of the 5 kg casting – Figure No. 13, for comparable production rates and size of chamber
  - Cost of dies = £1,600,000 – say £2,400,000 to allow for maintenance
- Cost of patterns for Alchemy Process = £50,000
- Savings to launch product = £2,400,000 – £50,000 = £2,350,000

When talking to Casting Buyers and Product Designers, one of their main complaints was the length of time taken to produce metal dies and their inflexibility to last minute changes. The need to manufacture only one set of patterns for the Disa, which are simpler to construct, not only reduces the lead time for new product introduction but also allows some degree of modification of a low cost.

**Casting Complexity**

The process lends itself to the manufacture of complex castings. An example of a casting produced on the prototype Alchemy plant is shown on Figure No. 14. Quotations were requested from a number of Die Casters to manufacture this casting, and the replies varied from declining to quote, to requests for modifications such as widening the fins, reducing the fin depth, being allowed to incorporate strip pin positioning points and concessions for impregnation. Using the Alchemy Process this casting can be made in greensand-at a production rate of two per mould and 360 moulds per hour i.e. 720 castings per hour.

In order to achieve the complexity of design in greensand moulds, the slim sections of sand must be able to resist the forces produced by the flow of molten metal. Referring to Figure No. 7 (b) it can be seen that the force on the sand cod is a function of velocity squared

\[ F = \frac{1}{2} \rho v^2 A \text{ divided by } g \text{ or } \frac{\rho v^2 A}{2g} \]

with a pump system the inrush velocity can be controlled to a speed of say 1 unit/sec as compared with a gravity system which would have a comparable velocity of say 6 to 12 units/sec. Taking the minimum gravity velocity of 6 units/sec the ratio of forces on the sand cod
using the $V^2$ factor is 1 to 36. It is this control of inrush velocities that allows a pumped system to produce castings that are complex or have a delicate structure.

The advantages of using the pump to increase flow rates at the end of filling to prevent short run defects and being able, if required, to decelerate at the point of final fill to prevent hammer, penetration and poor surface finish, are all positive features in producing complex castings. The pump’s ability to increase pressure, once filling has taken place and the metal is still molten, can be used to advantage in filling very thin sections. Development work is taking place to see, if maintaining the pressure at the end of filling, can be used to advantage in overcoming some shrinkage problems.

Pilot Plant and Early Development

There is only one way to prove a new process and that is to do it for real, in a working foundry, so in 1992 it was decided to build a pilot working unit in our existing greensand cast iron foundry incorporating a Disa 2130 mould machine. The plant consisted of a gas fired crucible melter, a radiant roof holding bath with a well pocket for the electromagnetic pump, a pump mounting carriage for movement, in-line with the moulds and at right angles to allow for alignment of the pump nozzle and the inlet to the runner. A computer was used to provide the variable programming necessary for the pump controls in order to satisfy the different filling profiles for a large number of different castings.

The first stage of the development was to establish an effective shut off device, for if metal pours out of the mould as soon as it is filled, then no progress is possible. After a number of designs were tried and rejected, a reliable and cost effective solution was developed which forms part of the patent application.

The next area to be addressed was that of the pump controls and feedback information, and very soon it was realised that conventional pumping systems would not meet the requirements. Most of the systems using pumps today are dedicated to one product or to another that closely resembles it, and once a filling profile has been determined mainly by trial and error then that is locked into the system as the standard. Some systems check the time of start and finish of the pumping cycle and this is considered to be sufficient control – what has actually happened during the filling process in this circumstance is still unknown.

In order to meet the wide range of products required by the industry and to take advantage of the Disa flexibility in production, it was considered to be necessary to be able to respond to a wide range of filling requirements, and the solution had to be quick, cheap and accurate. In order to achieve such an objective, it was necessary to change and develop the control system considerably, in order to obtain fast response to command and accuracy of metal delivery and this will be covered in greater detail in a later section. A great deal has been learnt about the design of runners, ingates and the effects of back pressure due to casting shape and metal velocity.

The pilot plant has been a great success, capable of demonstrating the production of a range of castings on a working Disa and this service is now available for the production of trial castings to potential customers of our new foundry. This is to be built as a specialised plant designed for the production of quality castings, in volume at very competitive prices. A big advantage of the pilot plant is that it allows ongoing development of controls, runner systems, process techniques and material properties whilst a new foundry is being designed and built. It is the intention of the newly formed company not only to sell castings but to sell the process and know-how to others for a commercial consideration.
Complete Controlled Filling of the Casting

From observations and trials, it is evident that all forms of gravity filling are not controlled over the whole of the filling cycle, nor can the fill rate be varied during the filling cycle to meet the exact requirement to maintain the critical velocity, and prevent the inclusion of air. Knowing the limitations and variables that take place in the metal delivery rate from ladles and autopours etc. combined with the limited knowledge of molten metal flow within castings, then all forms of software designed to forecast what is happening in terms of actual filling of the casting, are at best only an estimate.

The only true control system for filling castings is one that can control at all parts of the filling cycle and show evidence that what is being demanded is actually taking place – the Alchemy controlled filling is such a system and we believe it is unique in a production environment.

The accuracy of the control of the filling system cannot be determined until a way has been found to actually measure where the molten metal has reached at a point in time, and then be able to relate that information to where it has been designed to be. To support the design of gravity runner systems using cast iron, an electronic timing device had been developed using twelve probes which could be easily used in production and this was the fore-runner of a sophisticated unit which can measure twenty positions with a resolution of less than one hundredth of a second, and which can also record metal temperature. This instrument was christened "Wendy" by the team and is based on knowledge of "when do" metal has reached a point in the casting. Various techniques will be discussed later to show what an extremely valuable tool this is for designing casting filling systems.

Other research workers have used probes to detect metal entering a mould but these are usually confined to a laboratory exercise and do not entail many sensors. The "Wendy" system is cheap to construct (approximately £5) and it can readily and simply be used in production trials to prove filling programmes, which once proven, are locked into the control system for pump filling that particular casting.

Let us now examine how a casting is control-filled using the Alchemy Process. The selected example is shown in Figure No. 15 and Figure No. 16. On the right of Figure No. 15 the casting can be seen set out within the mould (a). This casting has a runner designed to allow containment of the advancing oxide film when moving at a velocity approaching the critical velocity. There are two ingates designed to suit the rule of junctions to prevent shrinkage problems and at the same time, minimising the amount of settling required. It will be shown later how the ingates are balanced to give a uniform rate of rise within the casting and prevent swirling. In the bottom half on the casting, the cross sectional area is small, then changes into a heavier section before advancing up two slim columns of small CSA to finally enter a very heavy section at the top of the casting. In order to fill this casting and maintain the critical velocity it will be necessary for metal to enter the ingates slowly (say 0.25 m/sec) so there is a low fill rate at this point. The fill rate in kg/sec can be increased in the lower half, but must reduce as the metal enters the two slim columns, in order to maintain the critical velocity. Once metal enters the large CSA at the top of the casting, the fill rate can then be increased until it is necessary to decelerate for end of fill.

It is the question advancing fronts in relation to oxide films, which is important as once the metal has filled a section its velocity can be increased without damage. For example, once metal has filled the two slim columns and has well entered into the heavy section at the top, the fill rate can be increased without any damage to the metal quality or incidentally to the mould itself.

The design logic of the filling process and how that is translated into the computer programme for controlling the electromagnetic pump, is now considered followed by how the programme is proven and corrected, if necessary.
Figure No. 17 (b) – This test indicates that all is not well with the filling system and splashing is occurring. The example shown is in a runner, but a classical example of splashing occurs in many gravity systems on the exit from the ingates when metal can spurt in the mould cavity bouncing off walls, and cores etc., in an uncontrolled manner.

Figure No. 17 (c) – The example shown is a simple check of actual velocity and by examining the time element over known distances it can be seen whether the metal stream is accelerating or retarding. This technique can be used to advantage at a change in cross sectional area within the runner system or casting which has also involved a change in metal delivery rate, say from 1 kg/sec to 3 kg/sec. The change of fill rate is not instantaneous and needs to be ramped up correctly, and the "Wendy" will show whether or not this is occurring too soon or too late.

Figure No. 17 (d) – Is a very useful check to show if the ingates are balanced and the casting is filling uniformly.

Figure No. 17 (e) – One of the techniques developed using a "Wendy" was to insert the probes into the core, in order to see what was happening internally, for example, to find out how tubes in a heat exchanger filled and why could short run appear in some unpredictable places.

The information gained from "Wendy" readings has convinced the author that the traditional methods of designing runner systems prior to using the pump system when working with a gravity runner system using cast iron are a poor reflection of the reality of what is taking place, and many old notes and text books have now been thrown away.

Some Comparisons Between Controlled Pump Filling and Gravity Systems

The difference between the two systems are numerous and touch on every aspect of manufacturing aluminium casting, so for the purpose of this paper reference will only be made to a few of the basic differences. The most fundamental difference is the ability to control the filling operation to suit the needs of the casting. Figure No. 18 (b) shows a typical gravity runner system filling a deep plate type casting. As the filling rate will drop off as the casting fills, the runner and ingate cannot be over choked, but must allow sufficient metal through at the start of the fill in order to maintain an average fill rate that will ensure the target time for filling is achieved. Therefore, systems have to have some degree of openness which allows the velocity due to gravity to play its part. Obviously a large runner system with very large ingates can be used which will slow the velocity down whilst maintaining the fill rate, but there are resulting penalties in the form of very poor mould utilisation, shrinkage problems and extra fettling costs. In Figure No. 18 (b), a velocity of 3 meter/sec fill rate has been used as this is not uncommon in many systems, to show the spurt height would be equal to 458mm, even at a velocity of 1 m/sec the spurt height would equal 50mm.

Looking at Figure No. 18 (a) which is a pumped system, the velocity of entry into the casting would be a maximum of 0.5m/sec which would give a spurt height of 12 mm which, incidentally, is the natural droplet height for aluminium. In order to be very safe, an ingate velocity of 0.25 m/sec is often chosen, this gives a spurt height of 3 mm.

It is interesting to note that on the pumped system the ingates can be reduced to suit the junction with the casting, also the reduced runner system gives an excellent utilisation and allows larger castings to be made in the same size mould.

Controlling the filling rate is essential for producing repeatable, reliable, quality castings and Figure No. 18 (d) shows a casting that requires variation to the fill rate, which cannot be achieved by the gravity profile shown in Figure No. 18 (e). The pump system shown in Figure No. 18 (c) shows the correct response to the filling requirements.


**Porosity and Material Strength**

The work carried out at Birmingham University, has shown the effect which cracks caused by oxide film break-up has on the bending strength of aluminium plates (Figure No. 5) and Lars E Björkøgen’s paper in the Hague in 1993 shows the relationship between porosity, and fatigue strength (see Figure No. 19 (a) and (b)), so there is a very clear message — if porosity is reduced the strength increases dramatically.

Porosity = oxide film inclusion + entrapped bubbles + shrinkage cavities + gas

The work carried out has shown that gravity filling systems are prone to oxide film inclusion and entrapped bubbles whereas the Alchemy Process overcomes these problems and resolves a major part of the problem with porosity. The use of a pump system can assist with certain aspects of shrinkage formation, such as working at lower metal temperatures, and better ingate design. Some of the causes of porosity start right back in the process, starting with initial melting and certainly with the use of some very crude metal handling systems. For the new foundry the melting process has concentrated on ensuring a smooth and tranquil flow from ingate to the pump well, and also in providing the ability to change alloys quickly and economically. A good metal melting and treatment practice will reduce hydrogen pick up to high quality standards and ensure that the total process is designed for the production of quality castings. How the advantages of greensand can be adopted to give good Dendrite arm spacing is the subject of another paper at the conference, and it is sufficient to realise that in greensand DAS can be within 5μm of die castings.

**Conclusions**

The production of castings of a consistently high quality, that are reliable in service, demands accurate control of the filling process. It is necessary to be able to design the filling sequence accurately and also provide proof that the designed criteria are being met.

All gravity filled systems fail in some way to provide the necessary control required, and many of the assumptions made and designs used in traditional gravity runner systems are at best only compromise solutions, and fall short of the standard required.

It has been demonstrated in the manufacture of complex castings that the Alchemy Process, with its fine control of pump delivery linked with positive feedback of the actual filling process, has set a new standard for the manufacture of a wide range of castings. Apart from high quality, the process has the following advantages to offer:-

i) Complexity of design  
ii) High volume  
iii) Short batch runs for JIT  
iv) Low cost tooling  
v) Quick new product introduction  
vi) Environmentally friendly  
vii) Low cost – competitive prices

**Acknowledgements**

Professor John Campbell, for the liberal use of his material, his involvement in the project from its first conception, and his belief we would succeed. The Alchemy Team for their dedicated commitment to the project and Baxi Partnership (Alfer) for allowing the paper to be presented and the cash to make it happen.
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Fig. 1 Current aluminium heat exchanger methods of construction

Fig. 2 Gravity Fill - Limited control of velocity, pressure and turbulence
Fig. 3 A schematic view of a splash of molten aluminium showing the formation of a folded (double) film which might consist of thick old film, or new thin film, or both, all likely to occlude air in the folds.

Inertial pressure $\rho V^2$ within the liquid -
(liquid density $\rho$ moving at velocity $V$) - balanced against
the restraining pressure $29\pi r \cdot \rho V^2 = 29\pi r$

Critical velocity $\therefore V = \sqrt{\frac{29\pi r}{\rho}}$

Fig. 4 Determination of critical velocity!

Fig. 5 Strength related to filling velocity [Ref. University of Birmingham]

Strength of present day aluminium components are greatly reduced due to process exceeding critical velocities.

Fig. 6 Gravity fill always exceeds the critical velocity at some point in the filling process.
Controlled Filling

(b) SAND STRENGTH

Metal
Flow
Velocity
Sand

(1) Force on sand = \( \frac{P \cdot A}{g} \)

(P = Density, \( A \) = Area)

(2) Effect of changing kinetic energy to pressure energy
\( \frac{W V^2}{2g} \)

(c) METAL FLOW - FREEZING

Force = \( \frac{P V^2 A}{8} \)

\( V1 = \sqrt{2gh1} \)

\( V2 = \sqrt{2gh2} \)

(d) BACK PRESSURE WHEN FILLING

\( \text{Pst} = \text{Back pressure resisting entry} \)

\( \text{Pst} = \frac{8}{(R + r)} \)

\( \delta = \text{Surface tension} \)

\( R + r = \text{The two orthogonal radii which characterise the local shape of the surface} \)

Fig. 7 Some of the problems with gravity filling
"Limited Control"

Stopper
Metal Level

Start of pour
Flow rate (Kg/Sec) = \( \mu \times \text{CSA/2gh1} \times C_d \)

Throttled position
Flow rate (Kg/Sec) = \( \mu \times \text{CSA/2gh2} \times C_d \)

Velocity at \( V_1 \): Start of pour - Aligned = \( \sqrt{2g \left( H_1 + H_3 + C_d + C_d + C_d + C_0 \right)} = X \)

Velocity at \( V_2 \): Start of pour - Misaligned = \( \sqrt{2gh_1} \) (\( C_d + C_0 \)) = Y

Fig. 8 Flow rates from autopours are subject to variation
Fig. 9  Some common pouring cups showing variation on filling

Fig. 10  Schematic of the mould which is covered by a glass-plate

(H. Nieswaag, H J J Deen - Delft University)
Controlled Filling

Fig. 11 Ingaling of horizontally and vertically poured disc type castings

- The production of high quality aluminium alloy castings
- Controlled anti-gravity filling does not exceed critical filling velocity
  - No oxide film inclusion
  - No air bubbles introduced
- Repeatable filling via control computer
- Volume production - up to 300 moulds / hour
- Low cost green sand moulds - recycled
- Low cost long-life tooling - does not come into contact with molten metal

Fig. 12 After — The Alchemy Process
Process Elements — (Patents applied for)
Fig. 16  Designed control filling with feedback

(a) Check on flow and runner design  
(b) Check for splashing  
(c) Check for velocity and acceleration  
(d) Check for balanced ingates  
(e) Probes inserted in the core to check filling of the tubes

Fig. 17  Some checks on filling using Wendy Technology
With a pumped system velocity through the ingate is controlled at lower velocity (< 0.5 M/Sec) at the start of filling.

\[ V^2 = U^2 - 2gh \]
Spurt height of metal \( h = \frac{U^2}{2g} \)
Say \( U = 3 \text{ M/Sec} \)
\( h = \frac{3^2}{2 \times 9.81} = 458 \text{ mm} \)

Fig. 18 Comparisons between systems pumped

Slow when required
Fast when required
Casting requires a slow fill at the start then faster, then slow, then even faster
Fast fill at start
Slow at end of fill

Fig. 19 Computed relation between fatigue limit, DAS, and amount of porosity (expressed in porosity grades according to ASTM E 155)
BJORKEGEN et al