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Metallurgy and Processing of High-Integrity Light Metal Pressure Castings

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5 High Pressure Casting Processes with Liquid Melts

In this work only those pressure casting processes are considered which apply hydraulic plungers to push the metal into the die cavity and solidify it after die filling under pressure. Processes such as CPC (counter pressure casting) with around 15 bar solidification pressure, gravity casting with pressurized feeders, and gas pressure infiltration with 80 to 100 bar (mostly used for the manufacturing of metal matrix composites MMCs) are not discussed in detail here.

An interesting new approach to combining the clamping unit of a HPDC or Squeeze Casting machine with a gas pressure unit for the manufacture of large size MMCs within a short cycle time was recently introduced by Schulz et al. [Schu04]. It presents the possibility for foundries to use their existing equipment to manufacture speciality products with limited additional investment. The attainable pressure in this system is about 200 bar. This is sufficient for infiltrating fiber preforms and particle beds smoothly and within a time reasonable enough to avoid preform compression and fiber/matrix reactions [Kau92, Kau93, Kau00a, Cap00].

In the following section the classical High Pressure Die Casting Process with a cold chamber is described in more detail; this is because many parts of a complete casting cell can be applied in an identical or similar manner in other processes. In describing alternative modern pressure casting processes the focus is on essential differences to the classical HPDC process.

5.1 High Pressure Die Casting with Cold Chamber

The casting cycle in a conventional High Pressure Die Casting Process on a cold chamber machine is shown in Figure 5-1. In principle, the same process flow is applicable to Al and Mg alloys. The furnace technology differs, however, because Mg melts must be covered with special protective gases to prevent burning.

5.1.1 Ladling and the first phase of the shot

First the melt is transferred from the holding furnace to the sleeve of the cold chamber machine. The cold chamber machine takes its name from the sleeve, which is surroun-

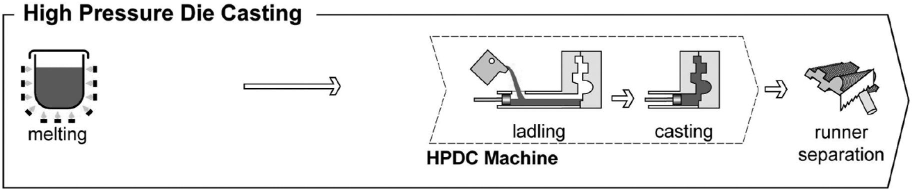

Figure 5-1: Process flow chart for conventional HPDC.

ded by air and kept at temperature levels (up to 250 °C) well below the solidus temperature of conventional Al and Mg alloys. During its sojourn in the sleeve, parts of the melt form a solid shell where the melt touches the sleeve and a rougher oxide layer, where it is in contact with the surrounding air. For the quality of the cast product this can be critical. Pre-solidified layers ("cold flakes") can even block the ingate area [Dai03, Kim01, Wan03, Wie03] or may be statistically distributed throughout the casting. These chunks of metal have different microstructures than the surrounding casting and are covered with an oxide film. They are preferred locations for later component failure.

Oxide films are believed to be a major source of defects in aluminium castings. Dai and Campbell [Dai03] report on "old" and "young" oxides, which can be differentiated by their thickness: roughly 900 nm on 99.5 Al after 20 hours at 700°C for old oxides, and around 24 nm after 5 min at 700 °C [Cam03] for young oxides. Since the ladling process and the shot take only a few seconds, only young oxides are created. Old oxides may be carried to the sleeve from the holding furnace, but there are ways to avoid creation of such oxides or keep their existence to a minimum (see Section 8.1 on melt quality).

It is to be expected that the ladling process may have a major influence on the temperature drop of the melt. Ladling includes the collection of metal from the holding furnace, its transfer to the sleeve and the tilting of the ladler cup for actual pouring of the metal into the sleeve. Usually the ladler cups are well heated, because they either rest above the radiating surface of the melt or are introduced into the furnace during metal pickup.

Wang et al. [Wan03] looked closely into the temperature drop of a melt during ladling. They used a cast-iron ladler cup with 6mm wall thickness, able to hold a maximum of 6 l Al melt. The fill ratio was only 40 %. They found a surprisingly low temperature drop of only about 8 °C during the transfer from the holding furnace to the ladling position.

Much more important than the temperature drop during transfer is the ladling flow profile and the settling time in the sleeve. They looked at three different ladling times (4s, 6s, and 8s) and the corresponding flow volumes of 1.91 l/s, 1.35 l/s and 1.07 l/s. The temperature at the inlet was 650 °C; it dropped by 20 °C during 4 s of pouring, 40 °C during 6 s and 45 °C during 8 s.

Once the melt enters the sleeve through the inlet hole it moves forward to the sprue post and forms a return wave. With faster ladling there is more metal splashing and therefore more entrapment of air and increased oxide formation. But this seems less critical to the authors than a longer waiting time in the sleeve. The first metal to enter the sleeve would have to wait 4, 6 or 8 seconds until the ladling operation is finished. During this time the melt cools down and solidification can start.

After ladling some foundries prefer to establish a settling time for the entrapped air bubbles to escape. Wang at el. [Wan03] checked the effect of zero, 1 or 2 seconds' settling time, while Benz and Klein investigated 2 and 4 seconds [Ben99]. They looked not only at the temperature drop, but also at the effect of pre-solidified layers on the flow behaviour of the melt during the plunger movement in the first portion of the shot (movement of the melt to the ingate). The temperature dropped an additional 15 °C in the first second and 10 °C in the 2nd second before the onset of plunger movement.

Modelling with the computer program “Flow-3D“ (www.flow3d.com) showed a significant alteration in wave propagation and the build-up of the return wave, plus a difference in the amount of entrapped air in the sleeve, when the settling time was varied and different amounts of pre-solidified layers were present. It was clearly visible that a zero settling time or a settling time as short as possible is advantageous [Wan03].

Benz and Klein [Ben99] performed an investigation of the influence of various sleeve and plunger materials on the formation of pre-solidified layers and on the quality of the final cast component. They supported their trials with results from solidification modelling based on the assumption of 65 % fill ratio of the alloy AlSi9Cu3 in a sleeve of 50 mm in diameter. It was shown clearly that, as to the amount of solidified metal before the start of the actual shot, insulating materials such as Hitachi Metals’ “Sialon“ ceramic or TYK Europe GmbH’s “Metacs TM6“ were superior to conventional steel sleeves comprising 1.2343 or 1.2344 hot working steel sleeves. The time expiring between completed ladling and the start of the shot is also crucial with these new materials, but they proved to be better than conventional steel sleeves. After eight warm-up shots and 2 seconds settling time after ladling 4.1 % of the alloy was solidified when Metacs was used, while as much as 13.2 % was solidified in the steel sleeve. 2 seconds later the amount increased to 8 % for Metacs and 27 % for steel. The authors calculated a temperature profile in the sleeve and the metal and found that after 8 shots the sleeve was in a thermal steady state condition. How the actual amount of solid fraction was determined was not well documented.

Wang et al. [Wan03] found around 0.7 % solid at the completion of pouring, 2.4 % after one second of settling and 5.3 % after two seconds of settling when the pouring took 8 seconds. In their study the metal temperature was 650 °C at the inlet, the sleeve was at 250 °C and the fill ratio was only 30 %. Contrary to expectations there was no significant difference in the amount of pre-solidified material between horizontal sleeves, as used in HPDC, or vertical sleeves, as used in vertical Squeeze Casting. A simulation with the computer program “ProCast“ (www.calcom.ch) was performed at LKR to clarify the details (Figure 5-2).

It was assumed that standard sleeves, which are available on the market, are used to cast 2.2 kg of the alloy AlSi7Mg. For comparison two sleeve diameters, 70 mm and 80 mm, were selected. In Squeeze Casting the sleeve filling ratio is always 100%, and the sleeve length is usually 50 mm longer than the metal filling height in the sleeve. This arrangement is achieved by adjusting a tip-joint in the plunger rod. The metal filling height was 228 mm and 175 mm for 70 and 80 mm sleeve diameters, respectively.

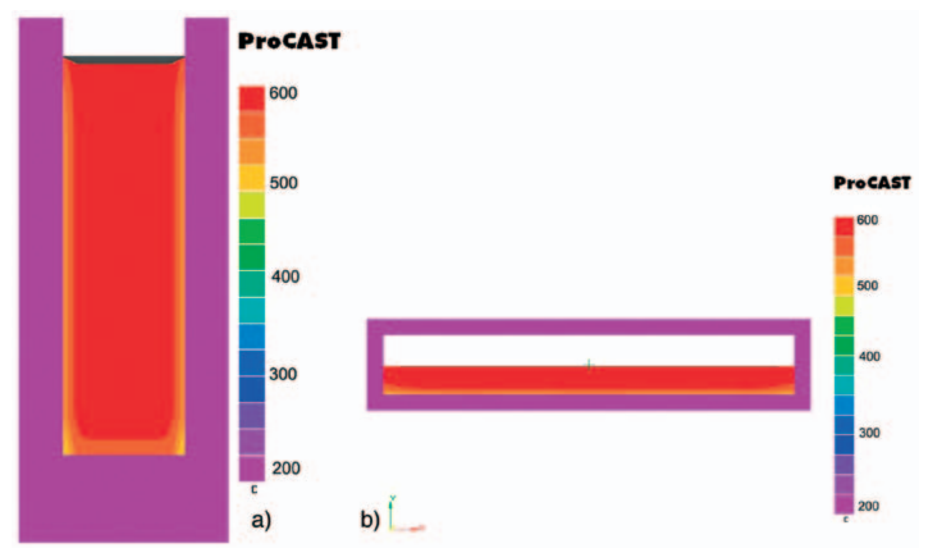

Figure 5-2: Arrangement for the calculation of pre-solidified layers in vertical (a) and horizontal sleeves (b).

In HPDC the filling ratio decreases with increasing sleeve diameter and constant melt volume. In the case described the HPDC sleeve length was 490 mm, leading to a filling ratio of 46.7 % with 70 mm sleeve diameter and 35.7 % with 80 mm sleeve diameter.

The steel sleeve was kept constant at 200 °C, and the contact area between steel and liquid metal was calculated to be almost equivalent for horizontal and vertical sleeves: 502 cm^2 for the 70 mm sleeve, and 440 cm^2 for the 80 mm sleeve. Bearing in mind that the heat loss in the sleeve is dominated by the contact area between melt and sleeve, the difference between the two arrangements in terms of contact area with the surrounding air is negligible (The heat transfer coefficient between melt and air is in the range of 20 W/m^2K, while for melt and steel it is in the range of several 1000 W/m^2K).

The cooling curve for the alloy AlSi7Mg0.3 was calculated via Thermocalc (Figure 5-3) and used to define the fraction solid at certain temperature levels.

It was the aim of this investigation to define the amount of pre-solidified surface layer in the sleeve prior to casting. This requires a definition of “solid layer“, since much more free-floating solid phase is present there than is connected in a stable layer. The authors decided to define the zone with at least 80 % solid fraction as the pre-solidified layer. This is a deliberate choice, since according to Dahle and St.John [Dah99] basically any value above 60 % solid fraction is the maximum packing fraction for small globular grains. Their measurements showed, however, that the strength of the structure is still very low at this level of solid fraction. Thus a minimum of 80 % solid fraction was chosen to reflect the idea of a shell-like layer of some mechanical strength.

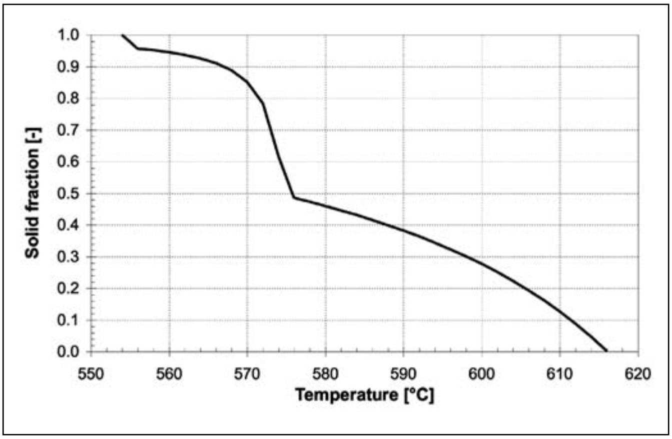

Figure 5-3: The cooling curve for the alloy AlSi7Mg0.3 was calculated using Thermocalc.

Three different pouring temperatures, T_P, were selected: 680 °C as the temperature of classical HPDC, 630°C as a possible temperature for Sub-Liquidus Casting (SLC®), and 608 °C to fill a slurry with 15% solid into the sleeve, as might be the case in the SSR® process. For details of the SLC® and SSR® processes cf. sections 6.1.4 and 6.1.5.

	HPDC Horizontal sleeve		Squeeze Casting Vertical sleeve	
T_P [°C]	D = 70 [mm]	D = 80 [mm]	D = 70 [mm]	D = 80 [mm]
608	21.9	19.9	21.6	18.6
630	16.4	14.0	13.9	13.5
680	10.8	10,5	11.3	10.0

Table 5-1: Volume fractionof pre-solidified AlSi7Mg0.3 layers with more than 80 % solid fraction in horizontal and vertical sleeves of 70 and 80 mm in diameter, depending on the pouring temperature. The dwell time in the sleeve prior to the actual shot was 4 seconds, and the sleeve temperature 200 °C. Considering the uncertainties of the simulation results, the pre-solidified layer in both types of sleeve is equal.

As mentioned, there is only a limited difference in the amount of pre-solidified metal between the vertical and horizontal sleeves in the selected, practical arrangement. For the given amount of melt it is recommendable to increase the shot diameter to 80 mm to reduce the pre-solidified layer. However, it should be noted that there is a significant difference in free surface, and therefore in the amount of surface oxides, between the two arrangements. The oxide layer in the horizontal die is roughly 6-7 times larger than in the vertical sleeve! These surface oxides are potential threats to the casting properties.

As can be seen from Figure 5-4 the pre-solidified layer (according to definition at more than 80 % solid fraction) is roughly 4.0 mm (!) thick when the slurry is poured at 608 °C and held for 4 seconds before the actual shot. Such inhomogeneous slurry in the sleeve must perforce have a negative impact on product quality.

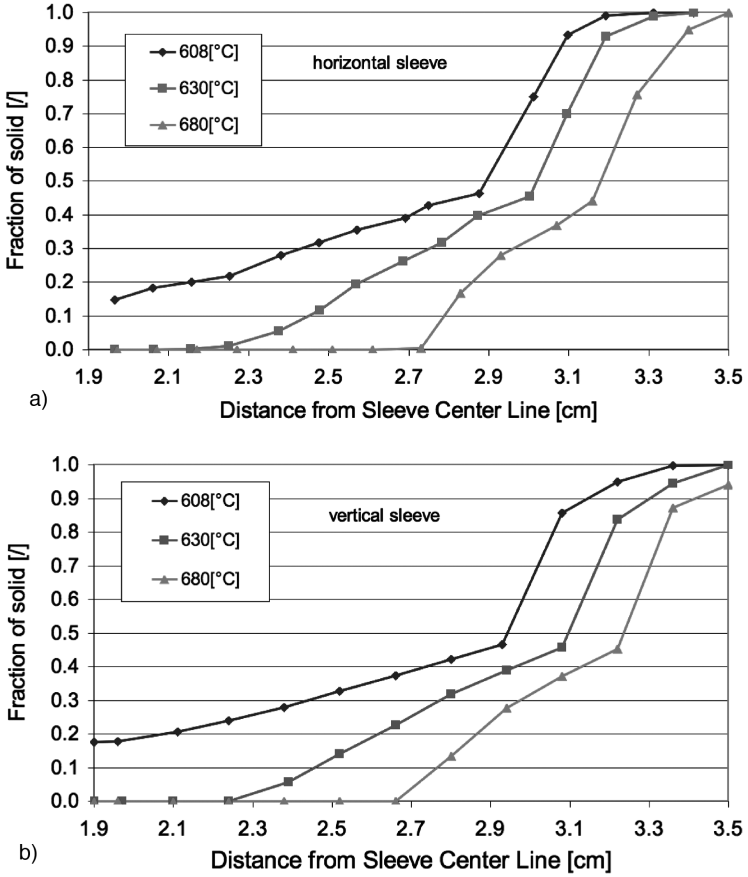

Figure 5-4: Relationship between fraction solid and distance from the sleeve wall (200 °C) for the alloy AlSi7Mg cast at 608 °C, 630 °C and 680 °C, with 4 seconds dwell time, for (a) horizontal sleeve and (b) vertical sleeve.

	HPDC Horizontal sleeve		Squeeze Casting Vertical sleeve	
T_P [°C]	D = 70 [mm]	D = 80 [mm]	D = 70 [mm]	D = 80 [mm]
608	39.4	38.0	40.6	35.2
630	29.4	25.9	28.6	23.0
680	21.5	18.3	19.7	14.5

Table 5-2: Amount of total solid fraction in the AlSi7Mg0.3 slurry in horizontal and vertical sleeves of 70 and 80 mm diameter, depending on pouring temperature. The dwell time in the sleeve prior to the actual shot was 4 seconds, and the sleeve temperature 200°C. Considering the uncertainties of the simulation results, the total fraction solid in both types of sleeves is equal.

A look at Table 5-1 and 5-2 shows that about half of the solid phase is present in the pre-solidified layer and the other half is free-floating in the slurry. For hypereutectic alloys the pre-solidified layer or phase contains primary silicon, which may in the long run lead to die erosion in the ingate area.

The ProCast simulation shown in Figure 5-2 assumed an even temperature distribution in the sleeve at the starting point of the calculation. In reality this is not seen. During ladling the melt flows down along the sleeve wall, experiencing some quenching. The first metal to enter the sleeve travels the longest distance in contact with the sleeve wall and also stays in contact with the cold plunger surface (maybe even resting there). The last portion of metal travels the shortest distance along the wall and never touches the plunger. After completed ladling the melt is expected to be hotter near the top than near the bottom of the sleeve. Upon die filling it is therefore the hottest metal which enters the die first. This is good, because this metal has to flow the farthest. This course of events differs completely from HPDC, where the coldest metal is near the gate at the start of the first shot phase. Measurements by Chen and Jahedi indicated that there was a temperature difference of roughly 125 °C for the alloy AlSi11Cu3 near the gate (475 °C) and near the plunger tip (600 °C) in a horizontal sleeve of a HPDC machine [Che98].

Benz and Klein also observed the positive effect on casting quality of insulating plunger tips. They concluded that insulating the plunger and sleeve helps to keep the melt liquid longer and makes feeding from the biscuit through the runner into the casting easier. Broken pre-solidified layers were again observed in the biscuit and the ingate area (i. e., also in the part!) [Ben99].

It may be added here that in HPDC feeding takes place when the plunger can still move forward after completed die filling to press liquid melt into the shrinkage area. If the biscuit is blocked with solid metal the plunger cannot move, and therefore cannot feed.

The influence of melt superheat on the number of “cold flakes“ (essentially, pre-solidified metal) in castings composed of an AM60 magnesium alloy in a cold chamber machine was investigated by Laukli et al. [Lau03]. In magnesium HPD castings fine- and coarse-grained structures are often observed adjacent to each other; they result from early solidification in the sleeve and at die walls during filling, and are redistributed within the casting due to turbulence. In Laukli’s work higher superheat reduced the amount of solid shells, but more floating grains were then observed. Titanium and TiB_2 grain refiner additions to the alloy AlSi7Mg led to an increase in the volume fraction of pre-solidified metal in the sleeve of an HPDC machine [Lau05a].

In the sleeve the melt may also pick up hydrogen, which can be detrimental to product quality. New methods of plunger lubrication (pellet lubrication) have been developed with the intention of protecting plunger and sleeve simultaneously, especially during ladling into the sleeve [Bed97]. Measurements of hydrogen content in HPDC parts with pellets and conventional plunger lubrication have shown that significantly higher levels appear in those parts made via the new method [Wie03].

The movement of the plunger in the first stage of the shot is very critical for casting quality. Generally the fill ratio of liquid melt in the sleeve reaches only 50% and is sometimes lower, while the rest of the volume is filled with air. If this air is trapped in the melt during the shot, the casting will show compressed air porosity and will not be heat treatable or weldable without blistering.

Stummer et al. [Stu90] point out that smooth movement of the plunger at the onset of the first phase is very important in establishing propagating waves in the sleeve. They use the dimensionless Froude number Fr to judge whether a wave will propagate away from the plunger to the sleeve and leave an air pocket behind which would then be compressed in the casting.

$$Fr = v/(gh)^{1/2} = v/c_0 \qquad [5\text{-}1]$$

In Equation 5-1, v describes the flow speed and c_0 the speed of the wave. It is valid for any ratio of wave length/filling height ≤ 16, as is common in HPDC [Stu90]. If $Fr > 1$ no wave would move away from the plunger and block the ingate. On this basis Stummer et al. developed a diagram as an indicator for the proper plunger speed in the first phase (Figure 5-5).

Both models assume a smooth pool of fully liquid melt in front of the plunger, which as shown by Wang et al. does not exist in practice [Wan03]. Propagating waves are present from the outset simply via the filling of the melt into the sleeve, and if the settling time is kept lengthy to smoothen the pool of melt the alloy will freeze. Therefore these models must be treated with proper scepticism.

In summary:

- With reference to ladling and the first phase of the shot, it has recently became clear that ladling and settling time after ladling strongly influence the temperature drop of the melt, the formation of pre-solidified layers and the wave propagation in the first phase of the shot.
- Since oxide inclusions and entrapped air or gases from cracked lubricants are detrimental to the product quality of high quality HPD castings, further efforts must be made to improve the current situation.

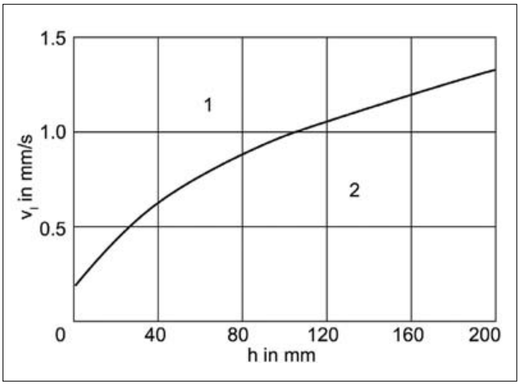

Figure 5-5: Regions with and without propagation of a distortion ahead of the plunger during the starting impulse. Region 1 shows no propagation, while in Region 2 a wave propagates towards the ingate. V is the plunger speed in the first phase and h the filling height of the sleeve [Stu90].

- Filling the sleeve can basically be treated like a gravity die casting process. A better “runner system“ for sleeve filling which keeps investment costs down and at the same time improves the flow to reduce surface turbulence and inclusions is required.
- This system is vulnerable because many parameters influence the outcome: alloy composition and fluctuations in the composition (see Chapter 9); fluctuations in ladling volume (= fluctuations in fill ratio) and ladling time; geometrical differences in the various ladler cups (different flow patterns during sleeve filling); ladler materials; sleeve diameter (= direct influence on fill ratio) and temperature; plunger temperature; plunger and sleeve lubrication; settling time.
- To keep uncertainty to a minimum, a careful choice of melt superheat is crucial. In the study of Wang et al. a total of 73 °C was lost between pickup to the onset of the shot (8 °C during transfer, 10 °C in the flow stream during pouring, 40 °C in the sleeve during pouring and 15 °C in the first second of settling). At the very least, foundries must check their systems and remedy this loss.

It is frequently heard that the situation in HPDC sleeves is similar to that in semi-solid casting, where an even higher amount of solid is present in the sleeve before casting. More on semi-solid casting is found below, but two comments are appropriate here. Firstly, in semi-solid casting the solid phase is globular in shape and can therefore move easily during die filling, while the pre-solidified layers are certainly dendritic and can block the flow. Secondly, the solid phase is distributed evenly throughout the melt in semi-solid casting, while cold flakes are not homogeneously distributed throughout the melt after compression, bending and cracking from the sleeve wall.

We have in the above concentrated on aluminium alloys. The situation is even more critical in terms of heat loss and premature solidification where magnesium alloys are concerned.

5.1.2 Die design and die filling

Figure 5-6 shows a sketch of a HPDC machine with a mounted die, indicating the essential parts of the equipment.

Usually a die consists of a minimum of two parts, one half mounted on the fixed platen (where the sleeve is docked to the die), and one half on the moving platen of the machine (where the ejector plate and the ejector pins are located). During die filling the dies are closed; after solidification of the casting the moving platen moves backwards to open the die. The ejector plate moves forward and pushes the casting from the die. Usually it is picked up by a robot, which grips the biscuit and transfers it to a trimming press or a saw to remove the runner system. Sometimes the machine ejects the parts onto a slide or even into pools of water, which may be located below the machine.

The runner system is a very crucial part of the whole casting. It consists of the

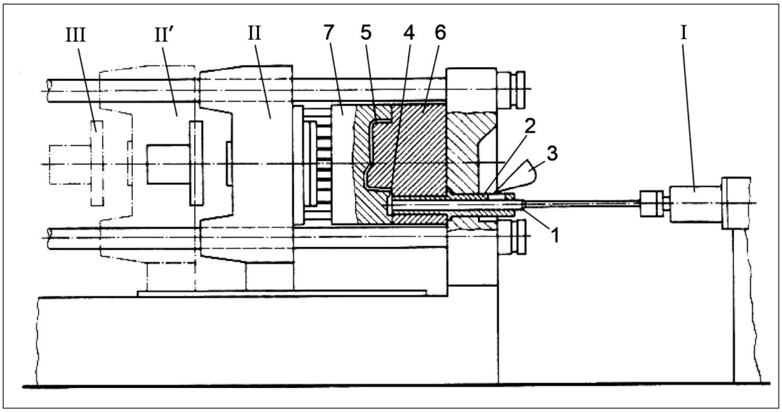

Figure 5-6: Essential parts of a cold chamber High Pressure Die Casting machine [Stu99]: I. shot unit; 1. plunger; 2. sleeve; 3. ladle; 4. ingate; 5. die cavity; 6. fixed die half; 7. moving die half; II. moving platen in closed position; II'. in open position; and III. ejector unit.

runner, the ingate and the biscuit. Its main purpose is to ensure the delivery of melt to all portions of the casting and allow feeding of metal during the solidification process.

The authors believe that attempts to standardize the design of gating systems failed in the past simply because of the complexity and the large variety of castings and machine combinations. In earlier days foundries tried a semi-empirical approach based mostly on the equation for mass balance:

$$A.v.\rho = \text{const} \qquad [5\text{-}2]$$

In equation 5-2 A describes the total gate area, v the gate speed and ρ the density of the melt. For incompressible fluid, this reduces to A.v = const.

Given a total volume of the shot (= casting plus runner, biscuit and overflows) foundries either calculated the gate speed by introducing an empirical filling time, or adjusted the gate area, the filling speed and the time until the set of parameters seemed appropriate. This is why a typical scrap curve over the lifetime of a die for any given part looked similar to that provided by [Stu90] (Figure 5-7).

The reject rate in the early phase of product manufacturing is very high due to improper die design and selection of shot parameters.

Only since the 1990s, with the aid of computer aided die design, flow modelling and modelling of solidification behaviour, has it been possible to define runner systems, gate areas, cooling channels etc. systematically for each given casting design. There is still much room for improvement (especially in the area of data for specific alloys, heat transfer coefficients etc.), but progress and the success rate in die design have been substantial. The shape of the reject curve will probably look like the one in Figure 5-7, but the absolute number of rejects will have been reduced, and the trial and error phase at the start of production will have been shortened.

As mentioned above there is no general rule for runner and gate design, but the

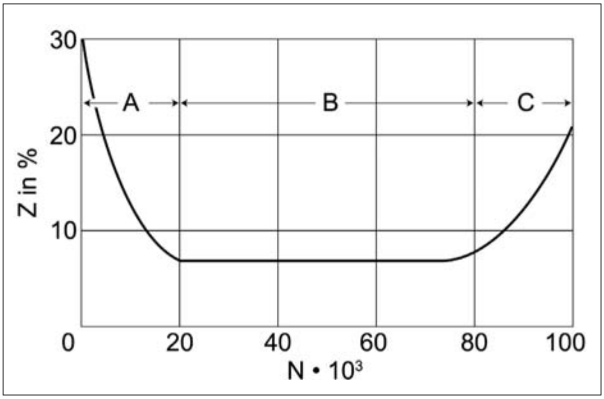

Figure 5-7: Reject curve Z plotted for the number of castings produced during the lifetime of a die [Stu90].

authors believe from personal experience that it is recommendable to gate at the thikkest portion of the casting and let the melt flow in the direction of thinner areas. That way there is a choice as to the size and shape of the ingate, and it is also possible to maintain the die filling time without premature solidification.

Referring to equation 5-2, we can state that a larger gate area would help to keep the flow speed low at a constant filling time. Remembering the Re and We numbers from Chapter 4, the chance for laminar flow is increased.

Sometimes foundries are unwilling to increase the gate area because of a trimming operation following the part extraction from the die. Kim et al. [Kim01] recommend 0.5 to 3 mm for gate thickness. The authors believe, however, that this is usually a bad trade-off, and recommend larger gate and runner sections for slower filling and improved feeding. A reduction in scrap rate and an extension of die lifetime (due to lower filling speeds!) is probably more cost-efficient than replacing sawing costs with trimming costs and possibly a slightly longer cycle time due to longer solidification time of the runner system.

Following this short digression into the area of die design we can now return to the die filling process. After ladling of the melt from the holding furnace into the sleeve of the cold chamber machine a hydraulically-driven plunger moves forward to introduce it into the die cavity and apply solidification pressure immediately after die filling. Basically all modern HPDC machines offer the so-called “shot control system“. This real-time system allows a shot curve to be set (plunger location versus plunger speed) and has the machine follow it [Ite92, Fin97].

Theoretically the plunger can accelerate and brake several times during one filling stroke. The idea is for the plunger to be able to move faster where necessary and brake, for example, just before obstacles (such as sliding cores), to avoid surface turbulence in the flowing melt. The optimized hydraulic valves have a reaction time of only 0.5 ms (!) and can therefore react fast enough to allow several changes of parameters during one shot [Fin97]. Considering that die filling strokes take only 50 to 500 ms the idea of changing the plunger speed frequently during one-shot stroke seems questionable to the authors, especially if the inertia of the melt is taken into account.

Interrupted shot experiments on a vertical Squeeze Casting machine during the filling of brake calliper castings illustrate this problem (see Figures 5-8). Fully liquid melts and semi-solid slurries of the alloy AlSi7Mg were cast into a single-cavity die at three different plunger speeds of 20 mm/s, 40 mm/s and 6 mm/s, respectively. These speeds are very low compared to those applied in classical HPDC, where even more than 10 m/s are applied. In addition, due to the bottom-up filling condition gravity should help to flatten the metal front, and suppress inertia flow at the interrupted shot. The location of the stop was selected such that just behind the stopping point a horizontal flow area would follow the bottom-up flow in the cavity; here a melt volume that moved forwards because of inertia could not return due to gravity. Figure 5-8 nicely demonstrates the differing behaviour of semi-solid slurries and liquid melts.

While the slurries stop at the interrupted shot position independent of the previous plunger speed, inertia forces the liquid melt to continue its flow despite the plunger stop. With increasing shot speed the continued flow distance increases, before final solidification halts it. This simple experiment demonstrates that changes in shot speed with braking and acceleration phases during one shot in high speed HPDC may not produce the intended result.

This is even more so when we consider fluctuations in the melt volume due to inconsistent ladling. Modern ladlers or dosing furnaces are supposed to transfer a melt volume +/- 1 % fluctuation into the sleeve. Practical experience shows that this is hardly ever achievable in the rough foundry environment.

Assume now that the plunger follows the set curve precisely and brakes in front of a sliding core. This may work if the melt volume is correct, but it may be too late or too early if there is only slightly too much or too little metal in the sleeve.

It should be mentioned that the brake calliper prototypes shown in Figure 5-8 were finally cast in New Rheocasting at a plunger speed of 100 mm/s. This low speed assured local Reynold`s numbers below 2000 and contributed to smooth, laminar die filling. The example illustrates the vast difference between the casting approaches in Squeeze Casting, Rheocasting and classical HPDC.

For improved process control the machine must know when the metal front reaches the ingate. Independently of the melt volume it could then run the shot curve for the moving metal front. Here fluctuation in melt volume would only lead to fluctuation in the biscuit thickness of the runner system, with no negative impact on the part quality.

Monitoring systems, which allow measurement of the melt position, are available on the market today. When the melt makes contact with a sensor this causes the electrical conductivity, pressure or temperature to change, which in turn provides a signal to the PLC and triggers the actual shot.

With regard to the problem of fingering this local measurement at the ingate is an

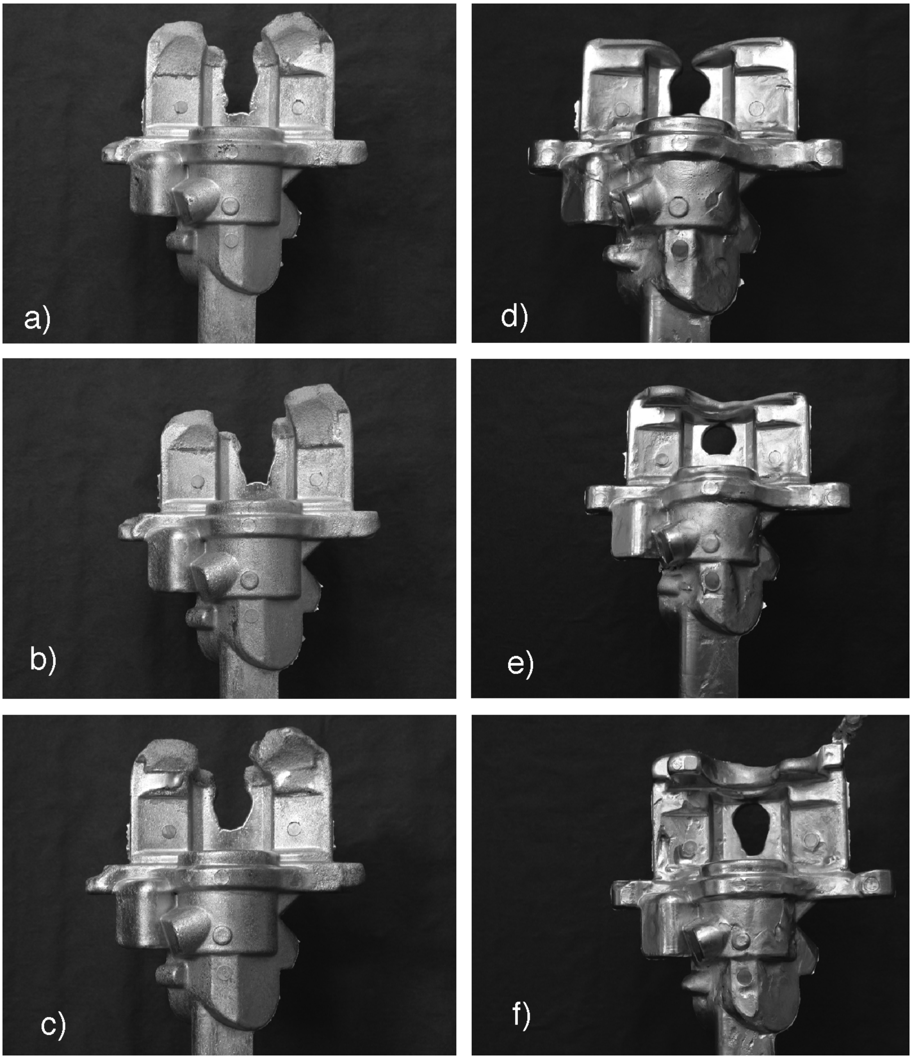

Figure 5-8: Filling front positions after interrupted shots following previous plunger speeds of 20 mm/s, 40 mm/s and 80 mm/s for the alloy AlSi7Mg: (a) 20 mm/s (b) 40 mm/s, and (c) 80 mm/s for the semi-solid condition cast at 50 % solid fraction; (d) 20 mm/s, e) 40 mm/s and f) 80 mm/s cast in fully liquid state at 700 °C.

improvement, but is still not perfect. In the best case the machine would know at any given time where the melt front is located in the die, and react properly.

Once the melt reaches the ingate the plunger accelerates and inserts the metal into the die at ingate speeds of often higher than 50 m/s. As described above, this is clearly in the regime of turbulent flow, or rather spraying. Entrapped oxides and gases are then compressed under solidification pressures between 500 and 1000 bar.

In the fabrication of thin-walled, large magnesium parts even lower pressure levels (around 300 bar) are sometimes applied. This allows casting of large parts on relatively small machines, which open their dies more quickly than larger ones, thereby helping to avoid cracking of the part due to shrinkage in the die.

5.1.3 Die lubrication and die soldering

Die manufacturing and maintenance make up more than 10% of conventional HPDC part costs [Pfo01]. If machine downtimes and reduced productivity are included in the discussion, the importance of good die function is obvious.

In the HPDC process die lubricants are normally applied before each shot to protect the die steel from erosion and soldering degradation. The tool steels most frequently used in HPDC die inserts are 1.2343 and 1.2344. Their chemical compositions are provided in Table 5-3:

Tool Steel	C	Si	Mn	Cr	Mo	V	S	Application
1.2343 X38CrMoV51	0.36	1.1	0.4	5.0	1.3	0.4		die inserts
1.2344 X40CrMoV51	0.39	1.0	0.4	5.1	1.3	1.0		die inserts
1.2312 40CrMnMoS8-6	0.40	0.40	1.5	1.9	0.2		0.08	die frames

Table 5-3: Chemical composition of tool steels frequently used in HPDC dies

In the earlier discussion of premature solidification in the sleeve of a HPDC machine we saw that sufficiently high superheat must be present to reduce this unwanted solidification, and that settling times should be avoided in order to gain a hot and mostly liquid melt flow. A fully liquid melt also hinders macrosegregation and banded defects. It was observed, though, that soldering most frequently appears in the region of the gate, where hot temperature, high speed and high pressure coincide.

It was mentioned previously that runner and gate design should render feeding of the casting possible right through to the very end of the solidification process. This is why the authors recommended gating at the thickest component section, and using a thick-walled ingate (to reduce flow speed and therefore turbulence). In terms of thermal and mechanical loading of the die this means that the ingate area would be in contact with the melt longer than all other die parts, and would usually experience the highest speed and pressure.

There has been a general belief that initial erosion strips lubricants and protective hard coatings from the dies, creating the danger of soldering of light metals to the die steel. There have also been frequent comments in the industry that soldering is a phenomenon characteristic of aluminium alloys only, but it has been nicely demonstrated that magnesium alloys with sufficiently high aluminium content will also solder to die steel [Tan03].

Chen and Jahedi [Che99] made a survey of critical literature concerning the process of die erosion and demonstrated very elegantly that many “general beliefs“ have either never been investigated in detail, or are wrong. For example, they looked closely at the common opinion that pre-solidified phases (such as primary Al in hypo-eutectic, or primary Si in hyper-eutectic aluminium alloys) can speed up die steel erosion (we are back to the subject of premature solidification and its negative effects!). In both cases they showed that the tool steel is significantly harder than the solid particles, and would therefore resist erosion.

In the HPDC of particle-reinforced alloys with SiC as a reinforcing phase ("Duralcan material") the situation may be quite different. In favour of this material type it has been argued that the SiC particles would always be covered with an aluminium layer due to the special wetting process required during the material's production, but this is questionable.

Table 5-4 provides an indication of the hardness values for various materials involved in the possible erosion process.

Hardness	H13 Die Steel	Aluminium	Silicon
HV at 570-650 °C	≥ 300	≤ 20	≤ 30

Table 5-4: Hardness values for H13 tool steel, primary aluminium, and primary Si in the range of 570 °C to 650 °C [Che99]

The literature review of [Che99] failed to find any experimental support for the view that a high filling speed would harm the die in the ingate area. Therefore they looked more closely at liquid impingement erosion, as studied closely in turbine plate erosion of steam turbines or in rain erosion of aircraft and missiles. Impacts in these applications reach transonic and higher speeds, which are significantly greater than the 50-100 m/s in the vicinity of an HPDC gate.

The most important theory for understanding the basic mechanisms of liquid impact erosion is that of guided acoustic shock (GAS). It describes the impact of a high-velocity liquid drop against a solid plane surface and the resulting two effects, impact pressure and lateral jet flow [Che99]. The average impact pressure of a liquid drop against a solid plane is the so-called water hammer pressure $P_{wh,avg}$.

$$P_{wh,avg} = \rho C v_i \qquad [5\text{-}3]$$

In equation 5-3 ρ is the density of the melt, C its acoustic velocity and v_i the impact speed. Data from various simulations indicate that the maximum pressure is lower than twice the average pressure.

The literature review suggests that the acoustic velocities for light metal melts have not been precisely determined; they may range from 1000-2800 m/s. With the assumption of C_{Al} = 2500 m/s and a gate speed of 50 m/s this generates an average pressure $P_{wh,avg}$ of around 340 MPa and a maximum pressure of 680 MPa. Even the maximum pressure is lower than the yield stress of H13 during die filling, which is in the range of 800 MPa.

Chen and Jahedi conclude that severe forms of liquid impingement and solid particle erosion are unlikely to occur in HPDC before soldering develops. However, they point out that long-term erosion is not yet well understood [Che99]. It was also observed that soldering can occur even after a few shots in the HPDC process.

This is where the chemistry of light metal alloys comes in, as an overwhelmingly important factor in the HPDC process and for product quality. It is generally acknowledged that soldering is closely related to the washout of a protective layer (lubricant or coating) on the die. The molten metal (aluminium or magnesium alloy) comes into contact with the die surface and iron dissolves into the melt. As a result, a layer of intermetallics is formed on the die surface. The formation of intermetallic layers is based purely on the diffusion and chemical reactions of elements in the die and the liquid metal.

The dominant process parameters influencing die soldering are [Sum02]:

1. Temperature of the metal and the die
2. Nature and constituents of the casting alloy and intermetallic layers
3. Die lubrication and die coating
4. Nature of the die (design) and operating parameters

Experimental results in the work of Han and Viswanathan [Han03] indicate that soldering between tool steel and liquid aluminium occurred at all temperatures higher than 657 °C. Figure 5-9 shows three typical cases from their work:

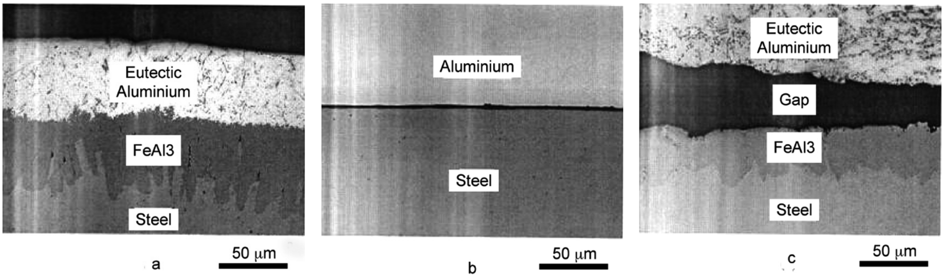

Figure 5-9: Three typical microstructures observed at the die surface for three cases: (a) metallurgical bond resulting in soldering; (b) absence of reaction between steel and aluminium; and (c) intermetallic formation on the die in the absence of soldering [Han03].

It is likely that the temperature at which or above which soldering can occur is the solidus temperature of the alloy produced when pure Al reacts with iron. For pure aluminium and steel this is the eutectic temperature of 655 °C, where Al and $FeAl_3$ form from the melt/steel reaction. If the temperature of the die is lower than 655° C everywhere, the phases will be solid and no soldering will occur. However, when the die temperature is above 655 °C a liquid phase will be present and soldering will occur.

For alloys the temperature at which soldering starts can differ from that of pure aluminium, depending on the alloying elements and their amounts. The discussion suggests that there is a starting point for soldering, if locally the die temperature T_D becomes higher than a critical temperature T_C, which is alloy-dependent.

$T_D > T_C$ [5-4]

T_C is the solidus temperature of the alloy that forms in the reaction with iron. It is always lower than the liquidus temperature of the cast melt and most definitely lower than the pouring temperature [Han03]. Therefore soldering will occur if the die is unprotected.

T_C can be calculated with the support of ThermoCalc. The data show that Ti, Cr, and Mn increase the solidus temperature, while Ni, Zn, Mg, Si and Cu lower it. Han's calculations agree well with the observations made by Shankar and Apelian [Sha02]. They suggest adding 0.125% Ti to the alloy and keeping the Ni level as low as possible. If this is done, the intermetallic layer is thin and the soldering tendency greatly reduced. It is also recommended to maintain an iron level of 0.85-1.15%, which is the saturation level of Fe in the melt at normal working temperatures. Care must be taken to avoid sludge formation in the furnace, which is enhanced by the presence of Fe, Mn and Cr in the alloy. It is reported in [Sha02] that sludge particles can act as nucleation sites for the formation of intermetallic layers on the die surface. (The subject of sludge formation is addressed in section 8.1, "Melt Quality").

The local die temperature T_D is most influenced by the pouring temperature, the geometry of the die and the casting, and also by surface roughness. Projections of the surface into the melt become hotter than the surrounding die areas.

Interestingly, little is known about the soldering tendency of magnesium alloys. It is often said that the low affinity between Mg and Fe is helpful in avoiding this problem. In reality the high amounts of Al in Mg casting alloys can also lead to intermetallic formation on the die surface and to soldering in Mg-HPDC. Tang et al. [Tan03] noticed in their work on soldering of various Mg alloys that intermetallic formation was linked strongly not only with Al, but also with the Mn content of the alloys. With alloys below 12 % Al no continuous layer of intermetallic was found on the die, when no Mn was present. When Mn was present, even in alloys with only 3 % Al such layers formed. They were generally poorly bonded to the die and appeared brittle. The major phases found on the substrates of tool steel dependent on the alloy composition are provided in Table 5-5.

Al content [at%]	Major Phase	Other Phases
3	FeAl (Mn,Fe)Al	-
6	FeAl	$FeAl_2$, Fe_2Al_5
8-9	$(Fe,Mn)_2Al_5$	$Mn_{23}Al_{77}$
≥ 12	$Fe_{14}Al_{86}$	Fe_2Al_5 V&Cr

Table 5-5: Aluminium content and phases found on H13 samples dipped into Mg alloys [Tan03]

Aluminium content is a decisive factor in the formation of intermetallic phases in the Mg-Al-Fe-Mn system. Manganese has a dual role in the formation of the intermetallic layer. It is present in the layer on the substrate surface at the initial stage of immersion and it also slows down the intermetallic reaction at a later stage by stopping or reducing the diffusion of Fe into the melt [Tan03].

From the above-mentioned investigations and the current status of knowledge in this field, the following procedure can be recommended:

Die design must be supported by modern simulation tools to optimize the flow and solidification behaviour of the metal in the cavity. Cooling should be optimized to avoid hot spots, which are especially prone to soldering. Parallel calculations with ThermoCalc should indicate the critical temperature of soldering for a given alloy. Adjustments should be made to the alloy, especially of Fe, Mn, Ti and Ni levels.

Unfortunately, the recommendations concerning alloy composition are not as clear as one would wish. Increasing iron content is detrimental to high ductility alloys, and a higher Ti level may increase hydrogen content in the melt and gas porosity in the casting (this matter is discussed later).

Higher levels of Fe, Mn and Cr would be helpful in avoiding soldering [Han03], but they also increase the amount of sludge, which seems to encourage it [Sha02]. Sludge formation can be suppressed with higher melt temperatures, but the latter lead to high contact temperatures in the die, which in turn favour soldering.

The pouring temperature should therefore be kept to a minimum, but premature solidification should be avoided. Again this is a conflict of interest for foundry men. New insulating sleeve and plunger materials may be a solution in the near future.

Semi-solid metal casting (SSM) lowers the contact temperature significantly and also delivers a much lower heat input to the die during series production of HPDC. This advantage of SSM is still underestimated. The target of increasing productivity is detrimental to the tendency for die soldering, since more heat is introduced into the die within a given time frame. This requires better thermal management of the die to keep T_D as low as possible.

The desire to cast net shape or near-net shape is accompanied by a reduction of draft angles on sliding cores and in other die areas. This causes more friction wear to the die surface. Scratches can add significantly to the problem of soldering.

Ch. Pfohl and K.-T. Rie [Pfo01] stated that the bonding between intermetallic layers and the die steel during soldering of aluminium alloys to steel is very strong. During part extraction from the die this may lead to material separation between the intermetallic and the casting or even in the casting. For Mg alloys Tang observed brittle and poorly bonded layers to the steel die [Tan03]. This means that such layers could also be on the casting and eventually create problems in later surface treatment steps (such as adhesive bonding of wooden layers on Mg castings in the dashboard area of modern cars).

Part manufacturing becomes even more complicated when steel inserts need to be cast into aluminium parts, and metallurgical bonding is the goal. In principle, die soldering and metallurgical bonding of inserts to the melt are very similar. If during one shot metallurgical bonding to an insert is the aim, and die soldering is to be avoided, additional measures must be taken. Die coatings and lubrication can help protect the die, while catalyst layers may enhance metallurgical bonding at the insert/melt interphase.

Coatings separate the molten aluminium from the die and help to hinder chemical reactions. Lubricants support the coatings by forming an additional separation layer. A closer look at this subject is found below.

In a recent investigation Hairy and Dussaussois [Hai04] looked at twelve new coatings for HPDC dies and compared the results with the winner of a previous investigation, PVD TiN. Based on the solubility of certain elements in aluminium melts at 700 °C most coatings are composed of boron, titanium, zirconium and chromium. Their solubilities are given Table 5-6.

Element	Solubility [%]
boron	0.06
titanium	0.15
zirconium	0.11
chromium	0.25
iron	3

Table 5-6: Solubility of pure metals in Al melts at 700 °C [Hai04]

The new coatings, from various companies, are mostly PVD and CVD. After laboratory and foundry trials PVD TiAlCrN (Nanocote 5 of the company Bodycote) and PVD TiAlN (Futura of Balzers) showed the best behaviour in terms of anti-soldering and scratch resistence, but the results were not significantly better than common PVD TiN coatings. All other new coatings showed worse results [Hai04]. Ch. Pfohl and K.-T. Rie [Pfo01] published an extensive literature review indicating possible lifetime extension of sliding cores via improved die coatings. In general they report the same results as mentioned above. PVD TiN, CrN, CrAlN and TiAlN delivered very good results. VC also showed excellent results, but was not investigated further due to critical environmental behaviour.

Based on a survey performed in 2002, the total cost of a coated sliding core can be divided thus: 4% steel costs, 30% machining costs, 3% heat treatment costs and an overwhelming 63% coating costs. The cost of a sliding core coated with PVD TiAlN would be around 110 Euro, and coated with PVD TiAlCrN 99 Euro [Hai04]. Therefore a significant extension of lifetime is required to balance the cost/benefit ratio for coated cores.

It should be noted that there is no mention in literature regarding HPDC die coatings containing Mg alloys. As mentioned before, the problem may still be underestimated, and has not yet received the attention of firms producing coatings.

Since the main purpose of die coatings is to hinder or prevent soldering of the melt to the die steel by prohibiting direct contact and diffusion of iron into the melt and Al into the die, any additional support is welcome. This should come from die lubrication. Lubricants create an interface between the die surface and the melt. They reduce the soldering tendency by assisting melt flow and casting release. Certain die lubricants can act as insulators and improve the die filling process by lower heat extraction. In almost all cases in HPDC practice, the spraying process is also used as a die cooling process. Die spraying is thus increasingly a cost and environmental issue for HPDC foundries.

Usually only 0.3 % of the whole spray volume consists of active lubricant, while 99.7 % is water [Bed96]. Lubricants stick to the die surface only when a proper wetting temperature is reached. Despite improved thermal management of dies, all too often spraying is used to cool the die surface before it can actually have any effect. Bednarek advises spraying the die from a minimum distance of 100 mm and maximum of 200 mm. When the spray head is too close to the die, the fluid hits the die at too great an impact speed and drips off without wetting the surface. If the distance is too great, the fluid drops become too big, lack sufficient impact pressure, and do not wet the surface either. The optimum die temperature after spraying would be between 180 °C and 200 °C, but it should always stay below 250 °C [Bed96]. The heat breaks down the emulsion and the water evaporates, thereby depositing lubricant onto the die surface. When the surface temperature gets too high (i.e., in hot spots), the surface energy of the lubricant material tends to increase, causing the lubricant to detach from the die and flow to areas of lower temperature [Sha02]. This exposes the die surface to liquid melt, and, after washout of a coating layer, soldering will commence.

The diverse soldering tendencies of different alloys also result in varying lubricant quantities. Wiesner [Wie03] reported an increase in lubricant quantity for the new Magsimal 59 alloy (AlMg5Si2) and for Magsimal 22 (AlMg2.5Mn), compared to the standard HPDC alloy AlSi9Cu3. This agrees well with the above-mentioned theories regarding the negative influence of Mg and the soldering tendency.

Graphite- and boron-nitride-containing lubricants are deployable at higher temperatures. Solid particles suspended in water are sprayed; again, the water evaporates and the particles stick to the die. These lubricants are a very good anti-soldering support, but in the authors' experience they can only be used with low-flow-speed casting processes: if the speed is too great, particles detach from the die and end up as brittle phases in the castings. These lubricants, however, are successfully used in Squeeze Casting and New Rheocastings and have allowed LKR to work intensively with pure aluminium melts under the worst of soldering conditions.

Dry lubricants are the latest development in lubrication technology. These are based on lubricant powders which are electrostatically loaded and therefore attach to the die. Since they avoid water-based emulsions or suspensions, the problems of water vapour and of hydrogen inclusions are greatly reduced.

Lubricants are also applied to the sleeve and plunger system to prevent sticking of the plunger in the sleeve caused by metal build-up. Normally the plunger lubricant is a mineral oil, and is applied from the back of the plunger. When the latter moves forward to cast a part, and on the return stroke, it delivers lubricant to the sleeve and into the gap between plunger and sleeve for the next shot. Newer plunger lubricants are placed as solid particles into the sleeve, evaporate above 130 °C and condense in colder areas of the shot system (i.e. in the gap between sleeve and plunger). Bednarek reports successful trials with the pellet ladler and an improved lifetime for sleeve and plunger units in industrial use [Bed97]. Wiesner, however, pointed out that this kind of plunger lubrication added extensively to gas pick-up in the melt before casting and to difficulties in later welding trials [Wie03]. Trials at LKR showed that the pellet lubricant may also be used in vertical sleeves, and with very limited pellet consumption to avoid too much gas inclusion for easy-to-cast alloys. The ladling of the melt was accompanied by short burning in the sleeve, which indicated that the reaction products had burned. When alloys with higher soldering tendency were cast, or pure aluminium was used, the pellet lubricant failed and led to sticking of the plunger in the sleeve.

Dies generally have air vents, and overflows are supposed to collect oxides. Additional venting is possible via clearing of ejector pins, sliding cores and the parting line of the die. One interesting side-effect of venting paths which is rarely taken into consideration should be mentioned here. Near the vents, where the die is open to the surrounding environment, there is hardly any increased pressure on the solidifying melt. This is why increased porosity is often observed beneath the surface of castings near venting slots. For this reason venting slots should be narrow, so that the metal can solidify quickly and solidification pressure build up. Venting slots are especially important in thin-walled areas of castings, where they alleviate the problem of back-pressure build-up and enhance die filling.

Sometimes it can help to deploy somewhat coarser lubricants to compress the air between lubricant particles. But if the casting is performed as described above (very high shot speed and turbulent flow), none of these measures will be sufficient to make ductile, weldable, heat-treatable castings. During heat treatment and welding, blisters will appear and ductility will be limited to 1-3 %.

In his Ph.D. thesis on the fabrication of weldable HPDC parts, Wiesner [Wie03] concluded that the quality of the melt in the holding furnace prior to casting in the HPDC machine has much less influence on the part properties than the time in the sleeve and the die during die filling. Figure 5-10 provides an overview of the possible sources of gas pick-up in the HPDC process.

There are several sources of hydrogen introduction into the melt, but wet spots from remaining lubricants and CH groups in the lubricants may be considered the most dangerous in terms of hydrogen pick-up. Nitrogen comes mainly from air trapped during ladling and die filling. For weldable castings for WIG/MIG welding the gas content should be below 10 ml/100 g, while conventional HPDC parts often show more than 30 ml/100 g. A lower consumption of lubricant helps to achieve the target value, but requires improved thermal management inside the die.

In the welding of HPDC parts nitrogen inclusions and hydrides cause major problems. Wiesner points out that dissolved hydrogen is generally no problem in welding, because the partial pressure is below 10 bar and usually below 5 to 7 bar due to diffusion of hydrogen in the solid aluminium casting. Nitrogen does not dissolve in alumi-

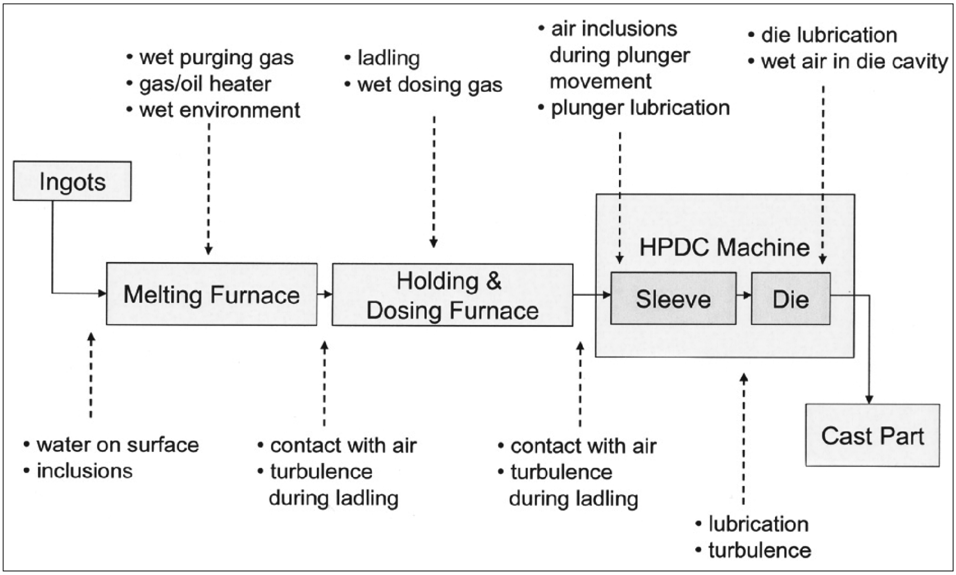

Figure 5-10: Sources of gas in HPDC [Wie03 quotes Nörenberg]

nium and is therefore entrapped under solidification pressure. This pressure of about 500 to 1000 bar is released quickly during welding and leads to explosion-like splashing [Wie03]. The same is true for hydrogen, which is present in the castings in the form of hydrides. Aluminium does not form hydrides, but some of the usual alloying elements do. Titanium and magnesium are major hydride-forming elements in conventional alloys. Calcium is also known for forming hydrides, as is the modifier Sr [Lee00]. At temperatures below 600 °C the capacity for hydrogen storage of hydrides is about 1000 times larger than the solubility of hydrogen in aluminium [Wie03]. This is why hydrogen-related porosity is hardly visible in castings. The big change in solubility of hydrogen during solidification is covered by hydride formation. Hydride-forming elements show a decreasing storage capacity with increasing temperature, while the opposite is true for solubility of hydrogen in aluminium.

Wiesner called this explanation a “working hypothesis“ [Wie03], but the authors of this book see strong evidence for its correctness in extensive R&D work on light metal foams in the LKR laboratory. A recently-presented work on the fabrication of magnesium foams via a melt-metallurgical foaming route uses scrap, litter, overflows and venting channels from HPDC as a precursor material [Kau04, Ren04].

In this new vacuum foaming technology (VFT) the above-mentioned precursor material is quickly remelted and then poured into a die, which is introduced into an autoclave and evacuated. Similar to the observations in the so-called reduced pressure test (RPT), the melt expands and bubbles form. The nice thing about this process is that it not only uses scrap, which is normally difficult to recycle, but that it actually needs this “bad“ material. The procedure will not work with common, clean remelted ingots or bulk material from the casting!

One part of the explanation – why the foaming process works - may be the expansion of entrapped air during die filling, according to the gas equation

$$pV = nRT \qquad [5\text{-}5]$$

In this equation p describes the gas pressure in the pore, V the volume of the gas, n the amount of gas in a gas pore, T the temperature and R the gas constant, which is R = 8.314 J/K.mol. In this ideal scenario surface tension effects do not counteract pore formation. An investigation is required as to whether expansion of entrapped air can be solely responsible for the significant pore growth upon evacuation which occurs. If the surrounding parameters are kept constant, a reduction in pressure increases the size of already-existing pores. As mentioned previously, nitrogen does not diffuse into solid aluminium or magnesium. Therefore, it may be assumed that the gas in the pores is compressed under solidification pressure.

During die-casting pressures up to 100 MPa are reached in the castings, and pores in the casting normally have the same pressure inside. After solidification the pore volume VDC does not change, and therefore the pressure inside the pores in the casting is:

$$p_P = p_{DC} \cdot T_R / T_S \qquad [5\text{-}6]$$

p_P is the inner pore pressure in the die-castings at room temperature, p_{DC} the pressure during die-casting, T_S the solidification temperature and T_R the room temperature [Str00]. When the casting is remelted under atmospheric pressure p_A the pores grow, reaching a pore volume V_M at melt temperature T_M:

$$V_M = p_P \cdot V_{DC} \cdot T_M / T_R \cdot p_A \qquad [5\text{-}7]$$

or

$$V_M = p_{DC} \cdot V_{DC} \cdot T_M / T_S \cdot p_A \qquad [5\text{-}8]$$

If a melt containing these pores is cast under atmospheric pressure, the pores in the casting will have a pore volume:

$$V_C = V_M \cdot T_S / T_M \qquad [5\text{-}9]$$

or

$$V_C = p_{DC} \cdot V_{DC} / p_A \qquad [5\text{-}10]$$

According to equation [5-10] the pores in the sample cast under atmospheric pressure (Figure 5-9) should have a volume 1000 times greater than that in the used scrap (Figure 5-8). However, as can be seen, there was no significant change.

A microstructure of the precursor prior to foaming is shown in Figure 5-10a. Pore sizes vary between 0.05 mm and 0.5 mm in diameter (assuming round pores). The pore volume fraction is in the range of 5-15 %.

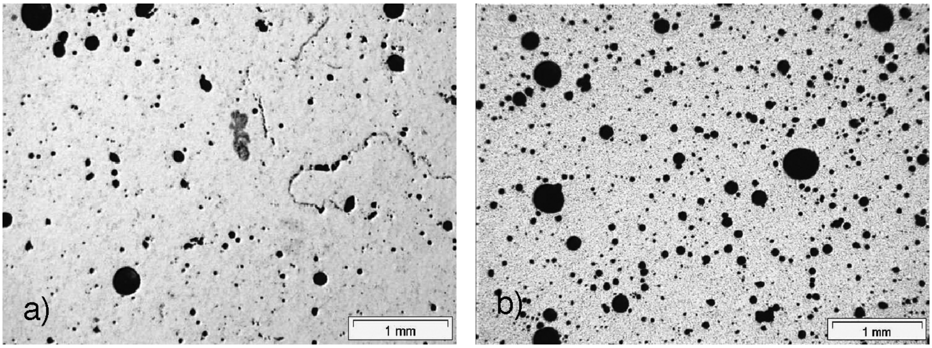

Figure 5-11: (a) Pore structure in HPDC scrap prior to remelting; (b) pore structure in precursor after remelting, holding for 10 min and solidification under atmospheric pressure. Pores and oxide films are visible [Ren05].

These scrap parts are remelted in a conventional foundry furnace. Surprisingly, the pore structure does not change much even if the melt rests in the liquid state for a while. This is shown in Figure 5-10b, and indicates that the melt is viscous enough to avoid quick bubble rise and outgassing at the melt surface. The pore size in the melt is about the same as in the precursor material.

Renger and Kaufmann propose two possible reasons for this observation: the flash and overflows usually solidify in well-vented areas with atmospheric pressure nearby; and/or the larger pores escaped the melt before casting [Ren05].

The VFT process works at a reduced pressure of about 0.1 bar, and according to equation [5-10] the pore volume grew by a factor of 10. Assuming a spherical pore, the diameter would have only grown by a factor of about 2.15. The resulting foam would therefore have pores in the range of 0.1 to 1 mm in size; but the pores in fact measure between 4-5 mm and in foams with low densities even more than 10 mm. This is the scenario in the ideal case of high pressure drop and neglected surface tension of the metal covering the pore. With the inclusion of surface tension, equation 5-6 can be modified to

$$(p + 2\sigma/r)\ V = nRT \qquad [5\text{-}11]$$

With the surface tension σ in the range of 0.5 to 1.0 N/m for Mg and Al, it can be seen that the pressure contribution is almost negligible for the diameters involved (2.10^{-2} N/mm^2 for 0.1 mm pore diameter).

This means that the original pores from the overflows should only grow to about 1 mm in diameter. The actual pores in the magnesium foam, however, are larger than the estimated pores resulting from air expansion. There are four potential reasons for this pore growth: (a) coalescence of pores due to rupture of cell walls; (b) additional gas entrapment with bifilms, when the machining chips were added; (c) decomposition of magnesium hydroxide $Mg(OH)_2$ from the scrap surface; and (d) dissolution of hydrides, which store hydrogen in the solid metal. It is very likely that more than one of these four processes are active simultaneously, and further research is required to clarify the mechanisms involved. While the process of foam evolution is not yet completely clear, these results are significant evidence that turbulent filling in HPDC causes gas entrapment and hydrogen pick-up. This reduces weldability and heat treatability, and causes the mechanical properties of the resulting products to deteriorate.

The concept of hydrogen storage in light metal alloys is also interesting for alloy development. If castings are heat-treated, but not welded, titanium and magnesium additions can help to avoid blistering. If castings are welded, the alloys should, if possible, contain no hydride-forming elements. Here we observe another possible conflict of interest for foundrymen. To reduce the soldering tendency of aluminium alloys, the addition of titanium to levels of about 0.125% is recommended. This can alleviate the soldering problem, but may cause trouble during welding. Where quick melting occurs during welding, TiH_2 dissolves and generates increased hydrogen porosity in the weld seam. In the Magsimal alloys MgH_2 may cause the same welding problem. Besides hydrogen storage, titanium also increases the viscosity of the melt and makes welding more difficult.

In designing alloys for melt metallurgical foaming routes, the solution may be alloys with increased Ti, Mg or Ca content. At 700 °C titanium can store about 17'500 times as much hydrogen as can aluminium [Wie03].

Hydrogen entrapment in light metal castings is generally considered a negative occurrence, but from the above arguments we can only say that this is conditional. For example, much depends on the actual use of the casting in its engineering function. Wiesner reported that dissolved hydrogen did not affect the mechanical properties of his castings at room temperature [Wie03]. If a HPDC casting is only used at room temperature or at slightly elevated temperatures, hydrogen inclusions may not damage its performance, and the simple die casting operation, without special measures to avoid inclusions and gas entrapment, may suffice. But if the casting requires solution heat treatment and welding, this no longer holds true.

An interesting issue is presented by the casting quality of “pressure tightness“. In low pressure die casting (LPDC) of aluminium wheels, it is common practice to add tablets to intentionally increase hydrogen levels in the melt (Foseco, for example, supplies such tablets under the brand name Hydral-40). Via this procedure, finely-dispersed hydrogen can counteract metal shrinkage during solidification and the wheel can obtain the intended shape and show pressure tightness in the leakage test. As mentioned above, the partial pressure of hydrogen in the pores is 5-7 bar. This means that 1 bar of solidification pressure in LPDC cannot suppress the formation of these pores.

Barnett et al. [Bar03, Bar04] used this method in gravity casting of intake manifolds for automotive engines, and observed that increasing hydrogen levels can actually prevent hot tearing, which was the main previous source of scrap. When they looked at the existing mathematical models for hot tearing onset and pore formation,

they found that both models suggest an increase in hot tearing tendency and porosity if hydrogen levels in the melt increase. These two models are:
Model for pore formation:

$$P_{sh} + P_g > P_{por} \qquad [5\text{-}12]$$

Model for hot tearing onset:

$$P_\varepsilon + P_{sh} + P_g > P_{ht} \qquad [5\text{-}13]$$

In the above equations P_{sh} is the pressure due to shrinkage, P_g is the gas partial pressure, P_ε is the pressure due to applied thermal strain, P_{por} is the sum of the pore-liquid surface tension pressure, metallostatic head pressure and atmospheric pressure, and P_{ht} is the sum metallostatic head pressure, surface tension capillary pressure and atmospheric pressure. Equation 5-13 was first proposed by Rappaz et.al. [Rap99].

Clyne and Davies introduced a cracking susceptibility coefficient (CSC):

$$CSC = t_v / t_r \qquad [5\text{-}14]$$

where t_v describes the time during which a solidifying metal is vulnerable to cracking, and t_r is the time where mass and liquid feeding is possible during solidification [Cly79]. According to them, mass feeding is possible in the range of 0.1 to 0.6 liquid fraction, while the metal is vulnerable to cracking in the range of 0.01 to 0.1 liquid fraction.

With these numbers in mind we should reconsider equations 5-12 and 5-13: if hydrogen tablets are inserted to add hydrogen intentionally, and there is sufficient hydrogen to exceed the storage capacity of hydride-forming elements at temperature levels below the liquidus temperature of any given alloy, pores will already form at the onset of solidification due to the reduced solubility of aluminium alloys in the solid or semi-solid state. This will therefore happen earlier than t_v, where only a small amount of liquid is left.

The pressure within these pores can eventually be sufficient to enhance feeding into the area which solidifies last, thereby helping to suppress hot tears from inside the casting.

If equations 5-12 and 5-13 are again applied to the situation in HPDC, it may be noted that the solidification pressure applied via hydraulic plunger replaces the metallostatic and atmospheric pressures and is several hundred times higher. This means that external pressure significantly reduces the hot tearing tendency.

The question is, can artificially-added hydrogen be beneficial in HPDC parts? High pressure and rapid solidification preclude significant hydrogen pore formation in thin-walled HPDC parts; and in thick-walled castings with longer solidification times pressure tightness may even be improved by increasing the hydrogen content. Again, however, all aspects of component requirements must be considered before taking such measures.

After this detour into the field of hydrogen solubility in light metal melts via reactions of die and sleeve lubricants with liquid metals, let us return to the subject of die soldering and address another important issue of die washout and soldering: dimensional tolerance and reproducibility. When Squeeze Casting and Semi-solid Casting became popular ten years ago, the foundry world liked the idea of net-shape production. "Net-shape manufacturing" signifies that no further procedure is required after the original shape-giving operation before the part can be used in an engineering system. The operation of machining to end shape is, in particular, cost-intensive. It was found, however, that with the new processes it was still generally impossible to produce net-shape components, which required treatment after casting. Therefore the term "near net-shape" casting was introduced. For some reason this term was associated with the new processes discussed later in this work, but it applies just as well to HPDC.

When we discuss stable processes we usually think of the productivity of a foundry cell, including the HPDC machine, robots for ladling and part extraction, lubricant spray devices, furnaces, etc. But it is very important to take the reproducibility of casting properties into our considerations. This wide field covers not only mechanical properties, but also surface quality and dimensional stability.

Dimensional stability is closely related to die performance. This returns us to the subjects of die washout and soldering. If there is severe die washout (after the protective coating has been washed out this may happen quickly) on a sliding core, the inner diameter of a bore may soon be the wrong size because the bore has become too wide locally. If there is metal build-up on the core, the bore will become too narrow locally.

It was mentioned above that there has been a tendency to reduce the draft angle on sliding cores to far below 1° to cast "near net-shape" or even net-shape parts. It was also mentioned that reduced draft angles favour soldering. It is assumed here that there must be an economically-critical draft value. The authors think that intentional machining due to a higher draft value increases the stability of the process, in contrast to after-the-fact machining to correct dimensionally-defective parts.

Die soldering generates an increase in the ejection forces required. When the ejector plate moves forward to push the casting from the die, there is little resistance if the lubricant and the die coating work well in combination with sufficient draft angles. Once soldering has occurred, ejection requires more force and may cause bending of the casting. In such cases the parts are either immediate scrap, or must be corrected dimensionally in a post-processing step known as "rectifying". This, of course, incurs major costs for the foundry.

Campbell points out that the size of castings also depends on the time to ejection [Cam03a]. Upon cooling the casting contracts onto projections of the die, and is forced to stretch plastically. Depending on the time to ejection, and the further cooling to room temperature, the dimensions will vary.

As mentioned above, in the past ten years the concept of near net-shape has been associated with semi-solid casting. This is mostly because contraction upon solidification in the die is less than in fully liquid casting. This does not tell the full story, however, because in HPDC, if shrinkage is taken into account properly during die design, the resulting parts are just as “near net-shape“. In terms of reproducibility there is an even higher risk of large scatter in dimensions when SSM is applied. As discussed in detail below, there are various sources of uncertainty connected with variations in the solid/liquid fraction of the alloy to be cast. Thus, if the reproducibility of the SSM slug is poor, shrinkage will also vary widely. Worst of all is the occurrence of the “sponge effect“. This is a separation of solid phase and liquid phase upon squeezing, leading to severe forms of macrosegregation.

After part ejection an automatic part extractor usually picks up the part and lifts it either into a quenching pool or onto a part conveyor. After trimming, cleaning and inspection the HPDC parts are finished and ready for shipment.

Post-casting operations such as heat treatment or welding are usually not possible with parts made via the conventional HPDC route. Additional measures for avoiding air entrapment and oxide inclusions must be taken. In the following paragraphs a closer look is taken at a few alternative casting routes.

5.2 Vacuum-assisted High Pressure Die Casting

Vacuum-assisted HPDC is just a logical improvement of the conventional HPDC process. A flow chart of the process is provided in Figure 5-12.

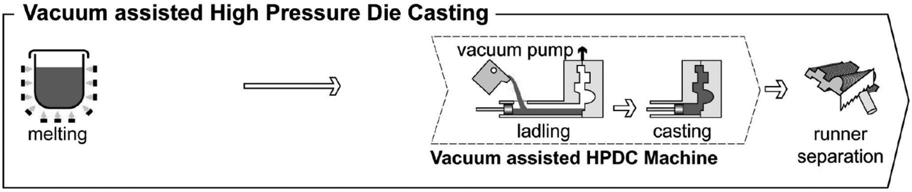

Figure 5-12: Flow chart of the vacuum-assisted HPDC process

VHPDC differs from the conventional HPDC process only in one point: an external vacuum pump is connected to the HPDC die. It starts operating shortly after the plunger has sealed off the sleeve inlet and pulls the vacuum either until the shot is finished or until just before that. Given the normal plunger speeds in the first phase of the shot (0.1-0.6 m/s) and the usual die filling times, only about 1.5 to 2.5 seconds are available for evacuation. This is a very short time, and high levels of vacuum cannot be expected. In literature various levels of achievable die pressures are given, ranging from 150 mbar (= $1.5 \cdot 10^{-2}$ MPa) [Wie03], $18 \cdot 10^{-3}$ to $28 \cdot 10^{-3}$ MPa [Niu00], 100 mbar (= $1.0 \cdot 10^{-2}$ MPa) [Wan04] and 200 mm Hg (= $26 \cdot 10^{-3}$ MPa) [Kim00].

Nevertheless, useful vacuum assistance can be applied during die filling of thin-walled castings by reducing the back-pressure of compressed air, and can be helpful in reducing entrapment of air and lubricant-related gas reaction products. Industry experts mention that it is possible to fill thin-walled cavities at a reduced filling speed compared to that of conventional HPDC, which is evidence of reduced back-pressure. Niu et al. reported a significant reduction of porosity in their sample castings compared to castings made by the same process without vacuum assistance, but admitted that it was impossible to avoid gas entrapment and gas porosity completely. One reason given for this was the false air pulled into the die via the die parting line and sliding core guides [Niu00]. In vacuum-assisted HPDC the dies are usually unsealed, and a flow of external air into the die is very possible. Wan et al. report leakage rates of roughly 230 mbar/s in an unsealed die [Wan04].

Kim et al. presented results from a study on the HPDC of an automotive component which required pressure tightness, and found that the best results were obtained by combining vacuum-assisted HPDC with one local squeeze pin in the die [Kim00]. Their experimental arrangement is shown in Figure 5-13.

There are different ways of shutting off the vacuum valve to prevent metal flow into it. Usually the valve movement is connected to the plunger stroke. For security the valve may be closed early, which shortens the effective evacuation time even further. The approach of Kim et al. is very elegant in using the well-known chill blocks to automatically seal the vacuum channel (see Fig. 5-13). When the melt reaches the chill block it eventually solidifies and seals the channel by itself, thus ensuring that the vacuum pump can suck air until the casting stroke has been completed.

Since Kim et al. had to cast parts with major variations in wall thickness, as indicated in Figure 5-13, they decided to apply a secondary plunger to push a squeeze pin into the solidifying melt to enhance feeding in this area. In their paper they present results from trials with delay time and squeezing pressure. These are very component-related, however, and cannot be taken as a rule for other castings.

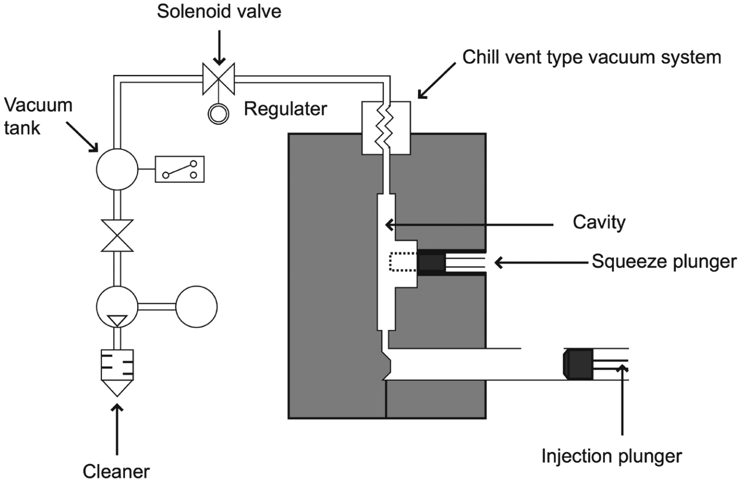

Figure 5-13: Schematic drawing of a partial squeeze and vacuum assisted HPDC machinery [Kim00].

From the drawing it can be seen that the casting has a thick-walled hub area in the center. Arrangements of this type can be found in brake discs, compressor scrolls, wheels and similar parts, and local squeezing may actually be useful. But partial squeezing must be regarded with some care. The authors performed some local squeezing work on Squeeze Casting machines, and discuss the process-independent findings below [Kau96].

With the increasing complexity of castings, and the attempts of designers to include more functions in one part to avoid joining operations over several parts, major changes in wall thickness in one casting are sometimes unavoidable. Despite optimized gating and feeding systems and proper die temperature management, shrinkage porosity due to poor feeding are inevitable in large part sections. In such cases partial squeezing may be a solution.

Usually the pins move forward after a set time following completion of die filling. In doing so they replace metal and push it into the area where shrinkage must be fed. However, there is a danger of introducing defects into the part which have resulted from oxide movement and the introduction of stress into the casting. Since the compression force near the squeeze pins is mostly higher than it is in the vicinity of the main plunger (similar hydraulic pressures are applied to much lower surface areas, $F = A.p$), the squeeze pin can act like a drill, and introduce microcracks or even shear off whole segments of the casting [Kau96]. In the vicinity of squeeze pins, macrosegregation (as in the sponge effect mentioned) is also sometimes observed. This is caused when the plunger moves forward and compresses the primary phase while the liquid eutectic phase continues to flow.

It is therefore essential, via close coordination of parameter setting and microstructural analysis, to determine the best time for the squeeze pin movement. Figure 5-14 shows the area around a squeeze pin in a casting, where a uniform crack at a distance of about 1 mm around the pin is visible. The squeeze pin was introduced too late (3 seconds after die filling was completed), and the pin sheared off a layer of material while entering the part.

If we assume that in this area of the casting a bore would have to be machined and a minimum of 1 mm would need to be taken off during machining, then this part may still be usable. But this may not often be the case; and the actual feeding support at such a late stage of solidification is also questionable.

If the squeeze pin starts to move earlier and faster (0.5 seconds after die filling and at a speed of 5 mm/s) the area surrounding the pin will not be destroyed, but will instead show a nicely deformed microstructure (Fig. 5-14b).

Since the selection of squeezing parameters is greatly part- and alloy-dependent, it is very useful to apply solidification modelling to reduce trial and error. Microstructural analysis is, however, the decisive quality-control step in the selection of suitable process parameters.

Another operational issue should be mentioned here. Since squeeze pins are fully imbedded in the die during die filling, and have to seal the die in this area, they cannot

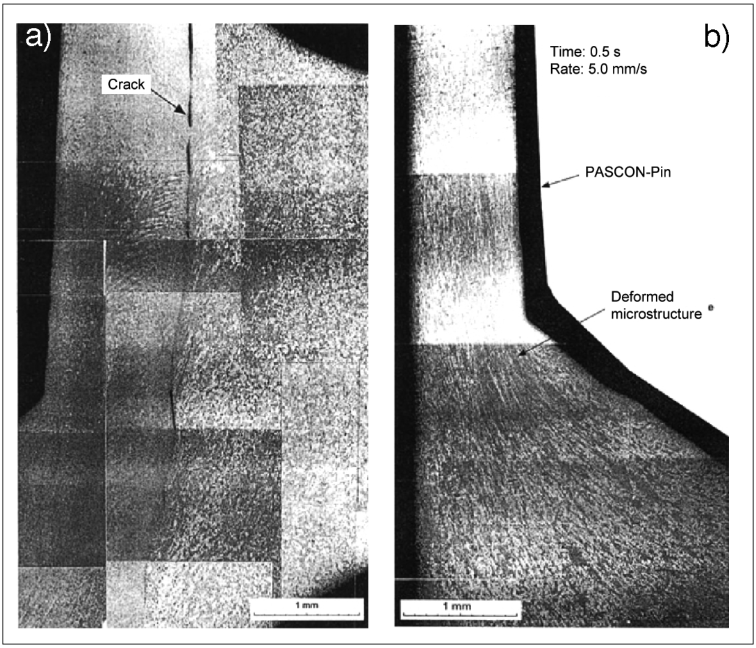

Figure 5-14: (a) Vicinity of a PASCON squeeze pin with the following squeeze parameters: start at 3 s after completed die filling, stroke speed 2mm/s; and (b) vicinity of a PASCON squeeze pin with the following squeeze parameters: start at 0.5 s after completed die filling, stroke speed 5mm/s [Kau96].

have a draft angle. When they move forward into the solidifying melt, they are prone to soldering. Here they are similar to any other sliding core in the die. Unfortunately, however, lubrication of these pins is more critical, because layers of lubricant may be scratched off the pin upon retraction and fall into the die, or pile up locally around the pin hole. During die filling the lubricant particles may be included in the part.

After partial squeezing the pin has to be retracted just like a sliding core, but it lacks a draft angle. Damage to the pin surface can occur quickly. Because of these operational difficulties, local squeeze pins have not been applied intensively in the field of HPDC, since they are a likely source of malfunction and machine downtime.

5.3 Vacural

Based on its experience with vacuum-assisted HPDC, the company Müller-Weingarten first developed a HPDC machine where the sleeve is connected to the furnace and the die and ladling and casting are carried out under vacuum (Figure 5-15).

Similar machines are now being used for the production of thin-walled, heat-treatable castings. Frequently slight modifications are made and then foundries give the process their own brand names (e.g. AVDC: Alcoa Vacuum Die Casting).

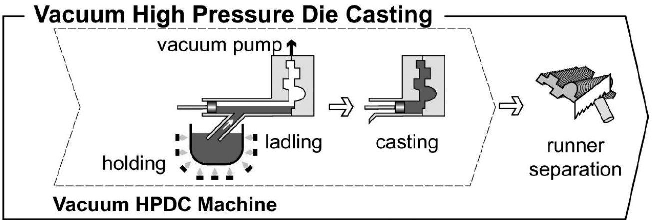

Figure 5-15: Schematic drawing of a Vacural HPDC machine, showing the connecting riser rod between sleeve and furnace, and the vacuum line.

In Vacural (or AVDC) the dies and the shot unit are sealed, allowing a much higher vacuum than in vacuum-assisted HPDC. Levels of 20 to 30 mbar [Had01] and 50 mbar [Wie03] are reported in literature. In addition, the leakage test exhibits a very low pressure increase of only 1.5 mbar/s [Had01], compared to the above-mentioned 230 mbar/s for vacuum-assisted HPDC.

Apart from this, the sleeve fill ratio and the shot speeds are essentially the same as in conventional HPDC and do not need further comment. Over the past ten years the technology has proved capable of making thin-walled, weldable and heat-treatable castings. The space frame nodes for the Audi A8 are a famous example.

5.4 High Pressure Die Casting with Hot Chamber

In hot chamber die casting machines the shot unit is immersed in a melt bath, and a pool of molten metal is maintained in the shot unit. This defined volume of melt is forced up through a goose-neck-shaped tube into the die. The die opening and closing direction is usually horizontal and resembles those in HPDC with cold chambers (Figure 5-16). This type of machine is generally used for small castings of magnesium and zinc alloys. For aluminium ceramic shot units would be required, to survive for longer periods within the liquid metal, while steel shot units can be used in the production of magnesium castings.

But even in the case of magnesium alloys the use of this apparatus is restricted to alloys with lower liquidus temperature, since the shot unit materials lose their strength and dissolve more rapidly above 650 °C. This is why only AZ and AM alloys are generally cast in hot chamber machines, while AS and AE alloys are cast in cold chamber machines [Lin00].

One of the advantages of hot chamber machines, however, is the fact that no separate ladling operation is required. This makes them attractive for magnesium casting, because it does not require contact between melt and the open atmosphere. Only after the development of magnesium melting and dosing furnaces for cold chamber machines did the use of hot chamber machines decrease.

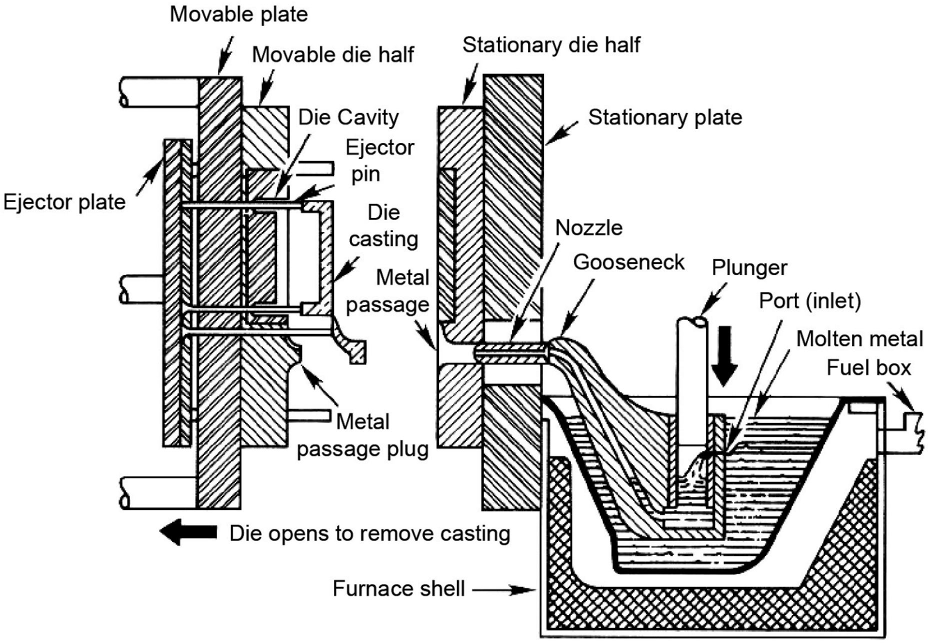

Figure 5-16: Hot chamber die casting machine showing a casting being ejected [Bra89].

Lindner compared the characteristics of hot and cold chamber machines for magnesium casting and summarized them in the following Table 5-7:

	Hot Chamber Die Casting	Cold Chamber Die Casting
Alloys	AZ91, AZ81, AM60, AM50, AM20	As in Hot Chamber, but additionally AE42, AS41, AS21
Casting Temperatures	Up to 650°C	Up to 750 °C
Shot Weight	Up to 2kg	Up to 25kg
Clamping Force	Up to 11 MN	Up to 50 MN
Spec. max. Metal Pressur	40 MPa	200 MPa
Cycle Time	12-45 s	30-120 s
Wall Thickness	0.8-3mm	1.5-12mm
Component examples	Mobile phone housing, radio covers, laptop covers	Gearbox housing, cylinder head covers, instrument panles, steering wheels, doors

Table 5-7: Comparison of Hot Chamber Die Casting and Cold Chamber Die Casting [Lin00]

5.5 Squeeze Casting

Squeeze Casting is a process involving slow filling speed, minimal turbulence and high pressure during solidification, which facilitates the production of heat-treatable castings of the highest quality [Elm94]. Low turbulence and heat treatability differentiate Squeeze Casting from conventional HPDC, but within this definition there is still sufficient room for process variation. Since product properties are the result of the whole processing chain it is therefore necessary, when technical results are reported, to name the respective squeeze casting process applied; in the following paragraphs the most important processes from the Squeeze Casting family are described in more detail.

Squeeze Casting is the most popular process for fabrication of metal matrix composites [Gho00]. Both direct and indirect Squeeze Casting routes are used for the infiltration of fiber preforms. However, the wide subject of MMC production is not dealt with in detail in this volume.

5.5.1 Indirect Vertical Squeeze Casting

The indirect Vertical Squeeze Casting process is a combination of bottom-up filling, familiar to us from LPDC, and high solidification pressures, even greater than those applied in HPDC. Filling the die from the bottom upwards ensures that the metal front is kept closed and horizontal with the help of gravity, as long as the critical speed for surface turbulence is not exceeded. The ingate speed of Vertical Squeeze Casting is roughly 1/100 of the speeds applied in HPDC. The process flow chart is provided in Figure 5-17.

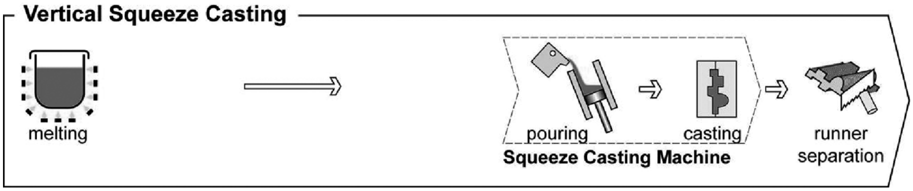

Figure 5-17: Process flow chart for Vertical Indirect Squeeze Casting (HVSC).

As early as 1979 Ube Industries Ltd. and Toyota Industries, Japan, reported the development of an indirect Vertical Squeeze Casting machine with a vertical shot unit and a vertical die clamping unit. This “VSC“ machine (Figure 5-18) was the first of a number of different vertical shot machines, the “HVSC“ machine being the most widely used (Figure 5-19). This HVSC type combines the vertical shot unit with a horizontal clamping unit as in conventional HPDC.

It is necessary to indicate the two different design variations, because they have a significant influence on the respective die design (discussed below).

A ladler (or a dosing furnace) takes the molten metal from the holding furnace and pours it into the slightly inclined shot sleeve (Fig. 5-17). When ladling is complete the shot unit moves into vertical position and is lifted to attach to the die from below in the so-called docking stroke. Following this movement of the whole shot unit, the

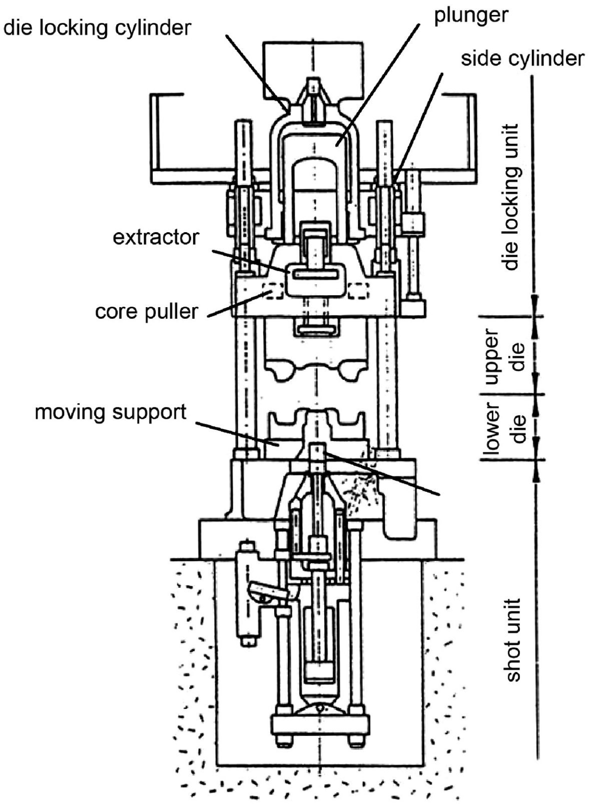

Figure 5-18: VSC - Indirect Vertical Squeeze Casting Machine with vertical shot unit and hydraulic vertical clamping unit [Kau96].

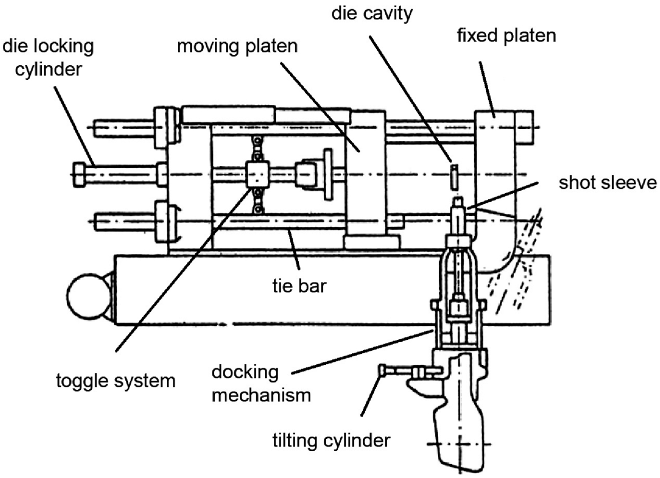

Figure 5-19: HVSC - Indirect Vertical Squeeze Casting Machine with vertical shot unit and horizontal clamping unit based on a conventional toggle system [Kau96].

plunger moves forward to push the melt into the die and subsequently to apply the solidification pressure. Following solidification the part is ejected and treated as in HPDC.

Entrapment of air and oxides should be avoided throughout the manufacture of high-quality castings. In Vertical Squeeze Casting the problems of turbulent lading (= gas inclusions) and pre-solidified layers in the sleeve therefore also need to be tackled. Ceramic sleeves (such as Sialon) are again a possible option. In addition, a clever ceramic ladling system has been developed which reduces the drop in melt temperature between holding furnace and sleeve, and is intended to support the filling of the sleeve with a minimum amount of inclusions [Yam94, Kau95a, Kauf96].

The so-called TF-ladler (= turbulence free) consists of a ceramic ladler cup (SiN) with a bottom hole and a ceramic center rod, which closes this hole. When the ladler moves into the holding furnace to pick up melt, the rod lifts and the melt can enter the cup smoothly from below. When the proper amount has been picked up, the ladler rod closes the hole. A robot lifts the cup from the furnace, carries it to the inclined sleeve, tilts the cup to align it with the sleeve and lifts the rod to open the hole for pouring (Figure 5-20).

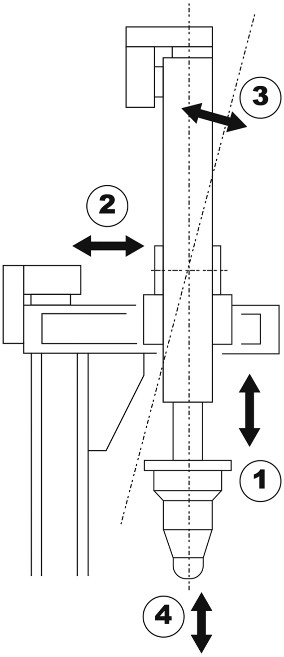

Figure 5-20: Ceramic TF ladler for vertical indirect squeeze casting machines [Kau95a].

It has been demonstrated in practice that this method is of help in producing high-quality castings. Hiroshima Aluminium was able to cast very large suspension parts (frames) in series production using it. They achieved long flow distances, because the metal temperature did not drop significantly during the transfer from furnace to sleeve [Kau95b, Kau96].

This technology also has disadvantages, however, which have so far hindered its wide use. The initial outlay is high, and so is the cup cost. Unfortunately, mishandling can lead to early cracking of cups, and foundries have thus preferred cast iron or other ceramic ladlers. In terms of keeping the melt temperature up, though, the concept has been a success. This is because only the very first metal to enter the die touches the cold sleeve and plunger, while the rest is introduced into the sleeve below the existing melt surface. While the sleeve is slowly filled, the cup is simultaneously retracted, but the pouring hole remains below the melt surface.

Usually the sleeve temperature is maintained at between 200 °C and 250 °C. The tilting and docking time is dependent on the machine size and is generally somewhere between 2 and 4 seconds [Kau96, Kau95c]. During this period a pre-solidified layer may develop which is similar to that discussed in the context of HPDC. However, there is one essential difference between the two processes: while the filling ratio is usually in the range of 30 % to about 50 % in HPDC, it is always 100 % in the vertical sleeve. Depending on the metal volume for one shot, the sleeve depth is adjusted by inserting a tip-joint into the plunger rod. This causes the ratio of sleeve length to sleeve diameter to stay in the range of 2. From experience this is a good value for minimum temperature loss and low sleeve distortion.

The layer of pre-solidified metal must be prevented from entering the die. Some foundries use steel mesh filters in front of the ingate to reduce the number of inclusions. These filters are either placed on top of the sleeve before docking and held in position between the lower die and the sleeve by the docking force, or they are bent into the ingate area, where the spring force holds them in position. The effect of these filters is questionable, because they do not really filter inclusions out of the melt but only cut them into smaller pieces. There is no real filter cake established in front of the filter.

Such filter cakes can, however, be built up within and in front of ceramic foam filters. Unfortunately, the latter tend to fracture during High-pressure Die Casting processes due to the high filling speed and the high pressure. Recent work at LKR has shown that it is possible to use ceramic foam filters in Squeeze Casting, if proper filter holders are used. Figure 5-21a and b show the results of Squeeze Casting experiments with ceramic foam filters, with and without proper filter holders [Schie05]:

In these Squeeze Casting experiments, Foseco filters Sivex*FC with 10ppi pore size were used to filter an AlSi12 alloy. Despite the fact that the casting speed was very low, the ceramic filter fractured when no filter support was provided (Figure 5-21a). When a filter support was used, no fracture was observed (Figure 5-21b). It can be seen, however, that increased turbulence due to the filter led to reproducible pore formation at the same place, just behind the filter. While these ceramic foam filters are said to support laminar flow in gravity casting, they obviously cause major turbulence when the speed is increased, as in Squeeze Casting.

While filters are a means of improving the melt quality of the alloy which enters the die cavity, they also increase product cost and make recycling more difficult. In addi-

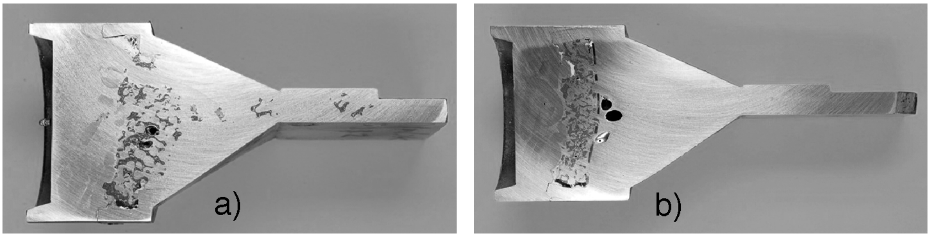

Figure 5-21: (a) Broken ceramic foam filter in Squeeze Casting on an HVSC machine. As shown in (b) a proper filter holder can prevent fracture, but in any case porosity was introduced behind the filter [Schie05].

tion, they may increase the cycle time if filter insertion cannot take place as a parallel operation within the cycle.

A proven method for reducing oxide inclusions and preventing the entrapment of the pre-solidified layer is the installation of a choke shoulder in the biscuit area [Kau96a]. This choke shoulder traps most of the pre-solidified layer before it moves into the runner system. However, its design leaves an outlet for the top oxide layer, whose final destination cannot be fully controlled.

By using spherical steel markers located in semi-solid slugs prior to re-heating and SSM casting, Chen et al. [Che99a] were able to show that the above-mentioned flow restriction via the choke shoulder actually works. Their experiments indicated, however, that those markers which were placed on top of the biscuit in the gate area and did not touch the choke shoulder moved to the highest position of the casting.

It can be assumed that this part of the slug moved into the runner system via "plug flow" without experiencing major shear and turbulence in the gate area. The observations also indicated that sufficient overflow area at the highest point of the casting can allow this top layer to move through the casting cavity and out into the overflow pockets.

It can also be concluded from this study that short, straight runners are not always ideal for casting quality. While the yield (ratio of part weight to shot weight) is certainly good, the chances of finding pre-solidified layers in the part also increase.

This problem can be solved immediately, however, if multi-cavity dies are used, where the runner normally has several corners to accommodate more than one part in the die. In multi-cavity casting it may be expected that parts of the relatively "old" oxide on the top of the slug (in SSM) of liquid melt (Squeeze Casting) will break up at the choke area or the subsequent corner in the runner system and stick to the wall of the runner, while the liquid melt passes by (this is similar to the normal break-up of "young" oxides at the flow front [Cam03]). Figure 5-22 indicates the theoretical model for the flow behaviour and oxide break-up of advancing metal fronts.

The design of dies with choke shoulders differs substantially between the HVSC and the VSC indirect Vertical Squeeze Casting machine types. The HVSC dies resemble the HPDC dies, but the ingate area is different. Figure 5-23 provides a general view of the die arrangement between the moving and the stationary platen of the machine.

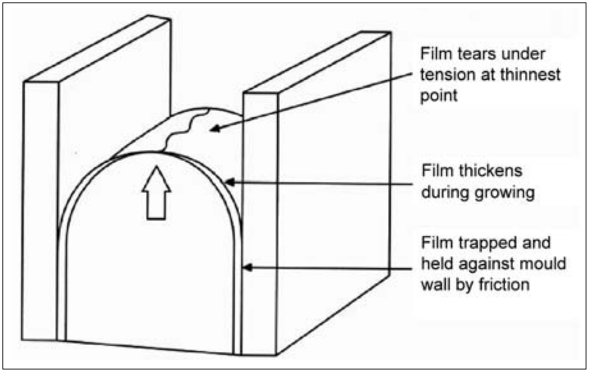

Figure 5-22: Rupture of the oxide layer at the advancing metal front during die filling [Cam03].

The die steel used is usually the same as in HPDC, namely steel grade X40CrMoV51 (1.2344) with a hardness of 40-44 HRC. The clamping force is calculated such that even without an additional fixture the die will not move upwards during the filling stroke and the solidification period. In any case, it is possible with this type of machine that the friction force, F_f, will be higher than the shot force, F_S. The friction force can be calculated from Coulomb's law by multiplying the clamping force F_C by the friction factor $\mu = 0.2$. In the case of an HVSC 350 machine, F_F would therefore be 0.7 MN, while the shot force reaches a maximum of 0.43 MN [Kau96a].

The choke shoulder for preventing or reducing oxide inclusions into the part can easily be machined into the HVSC die. Experience indicates that the shoulder should be 15 to 20 mm wide to be a sufficient barrier to the oxide flow and still leave enough room for the flow of clean melt into the die.

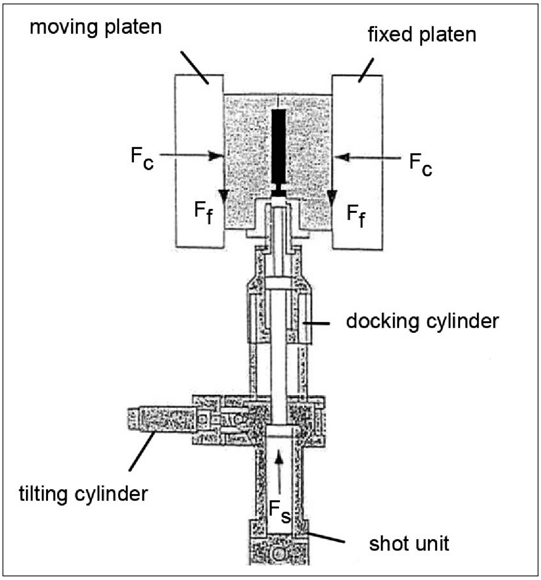

Figure 5-23: Die arrangement and shot unit in HVSC machines [Kau95c].

In contrast to HPDC, in Vertical Squeeze Casting the intention is not to have a thin ingate area. The main aim of gate and runner design is to keep the flow speed as low as possible, to stay below the critical values of turbulent flow (to avoid surface and bulk turbulence) but still keep the filling time short. This is only possible by increased volume flow via increased cross-sectional areas. As also recommended previously for HPDC, in Squeeze Casting the gate or gates are placed in the thickest portion of the casting to allow the connection of a runner system with a high modulus (high ratio of volume to surface of the flow channel), to ensure late solidification of the part.

The metal flow should then, if possible, move from thick to thinner areas. Taking into account the equations for Re and We, this means that the plunger speed should actually be reduced to stay below critical values throughout the casting process! This is not always possible in real casting, because an increase in viscosity due to ongoing solidification may require higher speeds (but may still allow laminar flow!).

Since the filling front is usually rather plain, the air can be pushed out of the die through venting channels and core clearances. It is seldom necessary to apply vacuum assistance in Vertical Squeeze Casting, although it can make sense in MMC manufacturing to reduce back-pressure in the fiber preforms. A familiar problem in infiltration of large preforms is when compressed air forms a pore in the center of an MMC. There is a significant pressure drop in the metal during the infiltration of dense preforms, which can in the end not overcome the back-pressure of the entrapped air.

It is helpful to achieve directional solidification by increasing the wall thickness towards the ingate and via a thermal gradient in the die. This gradient can be achieved with horizontal cooling lines with separate temperature control. In Japan, where most Vertical Squeeze Casting machines are in operation, this temperature profile is still

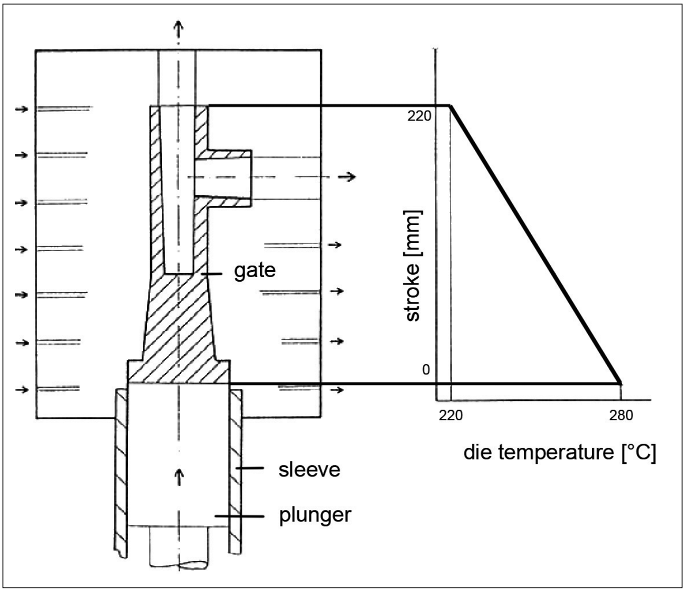

Figure 5-24: Thermal gradient for casting of a steering housing on an HVSC machine according to [Kau95c].

obtained by varying the flow volume of water through the cooling channels, while in Europe oil heating/cooling systems are generally used.

Figure 5-24 shows a schematic drawing of the die arrangement in an HVSC machine, together with an ideal temperature profile in the die and an ideal increase in the casting's wall thickness towards the ingate. This drawing represents an actual steering housing case made on an HVSC 350 machine.

If the solidification front moves towards the ingate area, the runner and the biscuit will solidify last. This is good for feeding, but limits the cycle time. Therefore, a solidification simulation can be again used to judge whether the solidified layer in the biscuit is strong enough for the die to be opened. This case is similar to direct chill (DC) casting, where the shell must be sufficiently solid at the exit of the die to avoid bleedout. In Squeeze Casting the shell must be strong enough to withstand the push of ejector pins and the grab of the extractor robot.

In VSC-type machines choke shoulders cause further problems in die design, because the part cannot be extracted without special measures such as sliding cores in the lower die half, as indicated in Figure 5-25.

After solidification is complete the sliding cores can be pulled and the part can move upwards with the upper die, before being ejected by ejector pins.

Another very sophisticated process is the application of a PASCON pin (see the

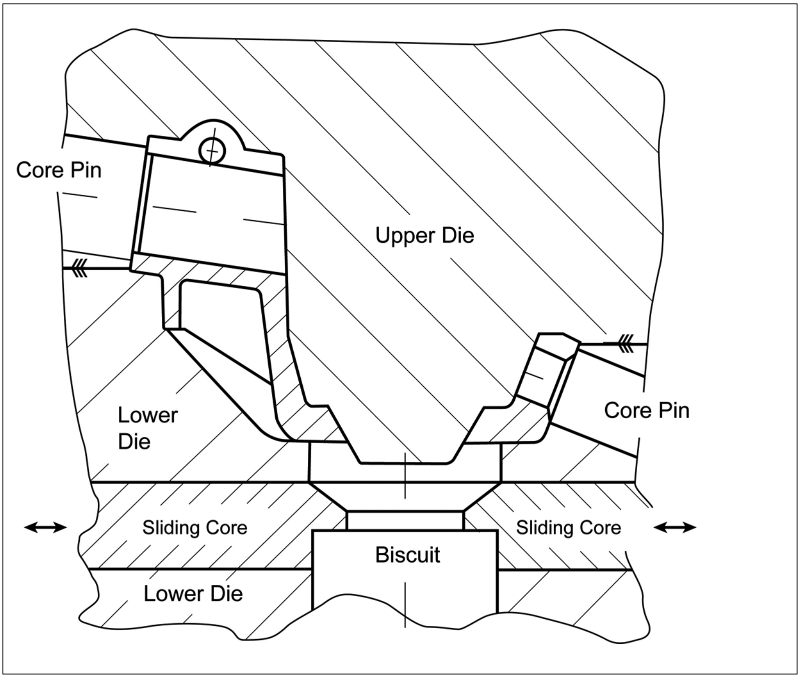

Figure 5-25: Die design for the casting of a knuckle on a VSC type machine, showing sliding cores in the lower die half [Str97].

section on local squeezing in vacuum-assisted HPDC) to enhance feeding and for separation of part and runner system in the die (Figure 5-26). This procedure is applied in the fabrication of Squeeze Casting wheels in Japan.

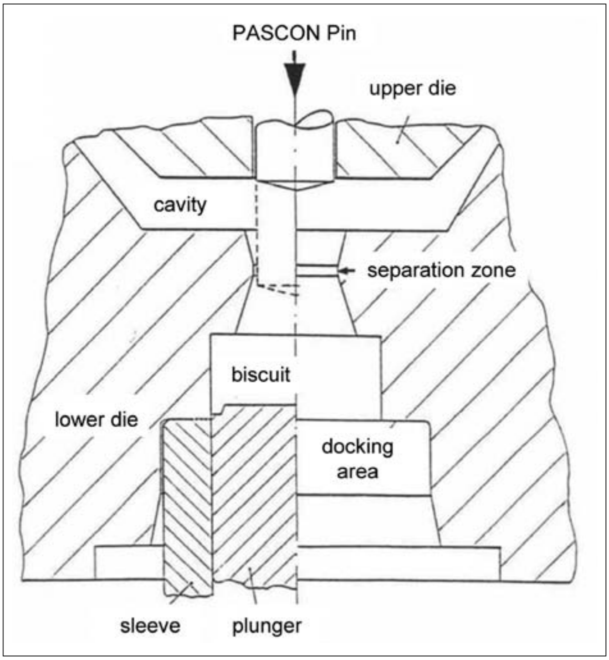

Figure 5-26: VSC die with central PASCON pin for feeding and gate cutting [Kau96a].

The PASCON pin is initially in a retracted position in the upper die, opening a wide flow channel during die filling. After solidification has progressed far enough the pin moves in a controlled fashion through the hub area of the wheel (which is the thickest portion of this casting) until it reaches a narrow separation area, where the casting is finally separated from the runner. A thin film of solid connection between runner and part remains, which is then broken during the die opening stroke.

The biscuit and runner drop from the machine onto a conveyor belt and are carried back to the remelting furnace. By applying this system the cutting operation outside the machine can be eliminated.

The two examples in Figure 5-25 (knuckle) and 5-26 (wheel) show, that VSC machines can be used efficiently for larger castings with central hubs. In the present case almost no runner is required, and the yield is quite high. While a 50 % yield is normal in HVSC casting, 70 % and even more are possible in this arrangement.

VSC machines have a hydraulic clamping unit, while HVSC machines have the mechanical toggle system of HPDC machines. The hydraulic clamping in VSC machines allows “two-step clamping“ for improved die evacuation. While the melt moves through the runner and the lower die half, the die is not fully clamped, thus allowing replaced air to escape through the horizontal parting line of the die. Just before the melt front reaches the parting line, full clamping force is applied to fill the upper die half and initiate the following solidification process. Since venting channels and overflows are not possible in the upper die, venting is carried out via ejector and sliding core clearances.

To facilitate this clamping trick, the flow speed must always be low enough to assure horizontal filling fronts without fingering. The knuckle made in the die shown in Figure 5-25 was cast with a plunger speed of only 80 mm/s (Str97]. This agrees well with the parameters published for other suspension parts. Yachi applied 40 mm/s for a knuckle [Yac91] and Fukube reports a plunger speed of 100 mm/s for the award-winning crossmember of a Mazda [Fuk96, Kau95b]. Compared to plunger speeds used in HPDC (nowadays 10 m/s and more), this is very slow.

As indicated in Figure 5-24, the die temperatures in Squeeze Casting are slightly higher than in HPDC. This is why different die lubricants are usually used. In Japan graphite is still the most common, while in Europe BN lubricants are more popular (they look “cleaner“).

Squeeze Casting is sometimes considered to be a slow process compared to HPDC. This judgement is usually based on the argument of slow filling, which is in fact ridiculous. It is really mostly just apples and pears, which are being compared, and hardly any investigation has been carried out into both processes on the same casting geometry. The authors, however, were able to perform such a study on a steering housing rack (see Figure 5-24), which was cast both on an HVSC 350 Squeeze Casting machine and a 400 ton HPDC machine with vacuum assistance [Kau95c]. The study showed clearly that there is a cycle time extension for die filling of about 1 second, and for tilting and docking of about 2 seconds. There is perhaps an additional second of extended solidification time due to higher die temperature, adding up to about 4 seconds additional cycle time.

This must be balanced with the significantly improved properties of the part. For the alloy AlSi9Cu3 in as-cast condition (= normal HPDC condition) the UTS was improved by 20 % from 162 MPa to 207 MPa, and elongation was doubled, from 1.2 to 2.4 %. These improvements can be attributed to the reduction in porosity level and oxide inclusions. The yield strength value, Rp, remained at about 130 MPa. After T6 heat treatment the Squeeze Castings showed 317 MPa for ultimate tensile strength, UTS, 258 MPa for Rp and 2.7% for elongation to fracture.

Yamamoto et al. [Yam92] report even better results for various compositions of the alloy AlSi9Cu3 by increasing its silicon and magnesium content and by reducing its iron level. In the T6 condition this alloy showed UTS of 423 MPa, Rp of 342 MPa and 4.4 % elongation to fracture in the cast test specimen. The potential of this alloy must be checked in other samples to confirm the extremely high values reported by [Yam92].

A special feature of Vertical Squeeze Casting is certainly the fine surface structure it produces, generated partly by the high solidification pressure and partly by the various lubricants. Sakamoto points out that wheels made by Squeeze Casting were very well-suited for producing the final shiny chrome-plating surface so often deman-

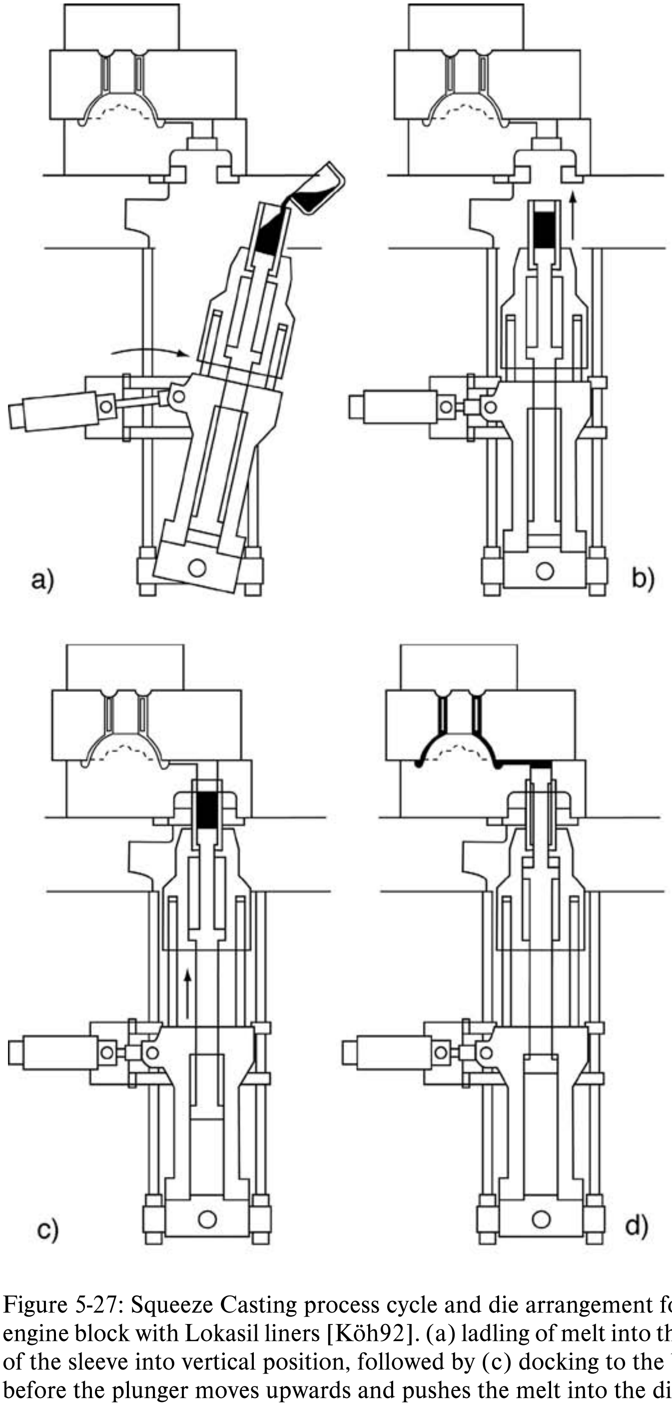

Figure 5-27: Squeeze Casting process cycle and die arrangement for a closed-deck aluminium engine block with Lokasil liners [Köh92]. (a) ladling of melt into the inclined sleeve; (b) tilting of the sleeve into vertical position, followed by (c) docking to the bottom of the lower die, before the plunger moves upwards and pushes the melt into the die cavity and applies the solidification pressure (d).

ded in the US wheel market [Sak94]. Compared to LPDC wheels one layer of Cu coating can often be avoided.

Köhler et al. pointed out that Squeeze Casting is also a suitable process for engine block casting utilizing Lokasil technology [Köh92, Köh95]. Again, the porosity of HPDC parts in areas near the surface is critical for any type of high-temperature coating. In Squeeze Casting gas porosity is reduced and elevated temperature treatments therefore pose no significant problem.

Lokasil technology is similar to the infiltration of fiber preforms. Local inserts of porous Si particles are infiltrated with the conventional AlSi9Cu3 secondary aluminium alloy to form a hyper-eutectic layer in the cylinder bore. Here the segregation of primary Si particles from hyper-eutectic alloys such as AlSi17Cu4 is replaced by the introduction of primary Si particles in the preform.

Figure 5-27 indicates the die arrangement and the filling cycle for an engine block with a Lokasil insert. It can be seen that in this case the central gating described for the knuckle part is not possible. With regard to the solidification pressures used in this project, special attention must thus be given to the mechanical loading of the four tie bars during solidification. Ideally these should be loaded with similar stresses. If they are, there will also be an even loading to the die and die life will be extended

5.5.2 Indirect Horizontal Squeeze Casting

Some researcher, realizing the potential of slow die filling for quality improvement of pressure castings, propose Indirect Horizontal Squeeze Casting based on the conventional HPDC process [Ite92]. Modern HPDC machines with proper shot control and strong shot units allow controlled slow die filling via larger runners and gate areas. Horizontal Squeeze Casting is therefore just a conventional HPDC process with a mere parameter adjustment, and nothing special otherwise. It should be regarded as a marketing strategy for HPDC machines, and is therefore not worth further discussion in this context. The technical explanations provided in section 5.1 for HPDC and in section 5.5 for Indirect Vertical Squeeze Casting apply fully.

5.5.3 Direct Squeeze Casting

In terms of machine design, the Direct Squeeze Casting process strongly resembles the forging process (see Figure 5-28).

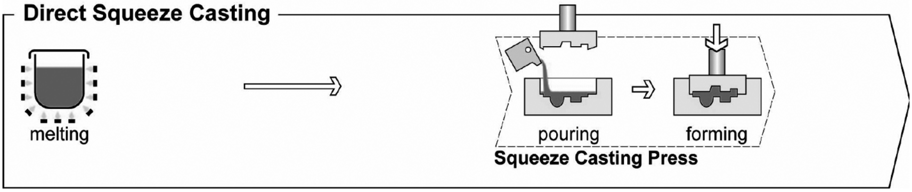

Figure 5-28: Process flow chart of Direct Squeeze Casting.

With the use of a ladler or a dosing furnace the liquid melt is poured into the lower die half, which has a horizontal parting line (the die arrangement is similar to that of forging). Once ladling is complete the upper die half moves downwards and applies pressure to solidify the metal. The upper and lower die halves form the outer shape of the casting.

While the principle of the process is very simple, the actual production of high-quality castings in terms of internal structure and dimensional tolerance is fairly difficult. The latter point is especially critical. Since there are no runner and biscuit system in Direct Squeeze Casting the ladling volume decides the final dimension of the casting. If the fluctuations in ladling volume of modern automatic ladling systems or dosing furnaces exceed tolerated dimensional fluctuations, the scrap rate will be high.

The proponents of this technology argue, on the other hand, that the yield is almost 100%, since there are no runners, biscuits or feeders. This is doubtless an advantage in terms of metal use, but not at all in terms of structural quality. Direct Squeeze Castings usually do not suffer from internal porosity, but from inclusions. A top-down fill into the lower die half, as indicated in Figure 5-28, is basically a bad example of gravity die filling. All oxides and bifilms, which develop prior to and during die filling, become part of the resulting casting.

Direct Squeeze Casting has not found wide application in the market. This is also due to the fact that only relatively simple geometries can be cast with this process. It is still used in trial casting of composite materials, however, and by some piston manufacturers.

5.5.4 Metal Compression Forming (MCF)

MCF combines Direct Squeeze Casting with Vertical Squeeze Casting in such a way that the entire mold face is pressurized [Col01]. The filling is bottom-up, and die clamping is horizontal, but the die insert at the moving platen of the die can act like a large plunger and put pressure on the solidifying melt.

The filling conditions are better than in Direct Squeeze Casting, but the complexity of the whole arrangement is significantly greater.