High pressure die casting (HPDC) die gating system consists of a biscuit or a sprue, a runner, a gate, overflows and vents. The biscuit forms in the cold chamber HPDC machine shot sleeve and sprue in the hot chamber HPDC die sprue bushing. Sprue bushing is an active element in guiding the metal flow. Cold chamber HPDC shot sleeve does nothing but offers a closed place to shoot the metal from.

There are two basic runner types: tangential and fan runner. (See images below.) Runner is a carefully designed part of the HPDC die. It controls the metal flow by accelerating and directing it to the right places inside the die.

Overflows gather the oxidised front of the metal and function as heat storage near thin and/or distant parts of the casting. Vents give the gases out of the die cavity. Short die cavity fill time requires more generous venting than longer fill time. Vents and overflows attract the metal front to the wanted directions, but mainly it is the runner, which does the directing.

Both runner types are widely in use. Tangential runner gives better possibility to guide the metal flow in the runner and inside the die cavity. It also gives better possibility to control the metal velocity in the gate and raise the velocity as high as wanted.
Usually foundry technical personnel design the gating system together with the die making company. The casting designer should be aware of the technical restrictions in gating to be able to produce cast friendly shapes. From the gating point of view, most important is to shape the casting so that the metal enters the mould cavity from one side, flows with direct and clear routes through the die and pushes the gases out from the opposite side of the cavity. Shapes, which block the metal flow or form closed cavities without venting, are not desirable. In some cases they are not even tolerable.

The gating design includes the following steps:

1. Analysis of the metal flow  
2. Selection of the best place for the gate on one side of the casting and vents on the opposite side and selection of a suitable die cavity fill time  
3. Division of the casting into gating segments  
4. Fill time and gate area calculations by segment; gate velocity selection by segment  
5. PQ analysis  
6. Modifications and a new tryout

1. Analysis of the metal flow

An ideal casting design allows the metal to pass the die cavity with direct and clear routes. Usually there is a need to compromise. Only seldom it is possible to design an ideal gate and runner system. (See images.)

Image 3. A cup-shaped casting with a flange. Metal flow starts from the parting line and finishes to the parting line on the opposite side. No large bosses outside or inside. Clear flow pattern and enough space for the gate.

Image 4. A flat casting. No high bosses. Clear route. There are blind spots behind the holes in the end of the metal flow path. Metal enters the last point from two directions and it is possible that there will be an area where the mechanical properties are not as good as on the other areas of the casting.

Image 5. A casting with cooling ribs. This is not an optimal solution. Ribs form closed cavities outside the main route of the molten metal.
Possible casting defects:
If the metal does not flow efficiently through the cavity it is likely that the castings will have **gas porosity**, **gas bubbles** or even large **voids** in the problem areas. Blind projections do **not fill properly**. For example the cooling ribs in the image 5 do not fill with ease. One solution to the filling problem is to use vacuum valve or to adjust the casting shot pressures carefully. Castings with shapes, which fill with the metal flowing from two directions, tend to form **cold flows**. The casting in the image 5 might end in having cold flows behind the holes in the last filling parts of the casting. Below are images of these casting defects.

Casting defects resulting from poor flow profile
Image 11. Left: Cold flow and flow lines. These will occur if the metal temperature drops too low before the die cavity is totally filled. Right: A non-fill in a cooling rib. Possible causes a poor venting or bad shot parameters.

2. Selection of the best place for the gate on one side of the casting and vents on the opposite side and selection of suitable die cavity fill time

Fill time
The casting should have enough space on the parting line for the gate and vents. The gate length is the gate area divided by the gate thickness. The gate area depends on selected die cavity fill time and gate velocity. Die cavity fill time is selected on the grounds of:

- **Thinnest casting wall thickness**: Thick wall allows longer fill time than a thin wall. Thin walls tend to solidify prematurely if the fill time is too short. Also the flow length is critical. If there are large areas of thin walls or the thin walls are in distance from the gate, the fill time must be selected shorter.

- **Thermal properties of the casting alloy and die materials**: Liquidus temperature, width of the solidification range and thermal conductivity of the mould material. These influence the solidification time.

- **Combined volume of the casting and overflows**: Thin wall castings, castings with long flow distances through the cavity and castings with special surface quality requirements need large overflows. Large volume of the metal is able to keep the heat longer than a smaller volume.

- **Percentage solidified metal allowed during filling**: The better the wished surface quality the less solidified metal is allowed and the shorter the die cavity fill time.
One of the best known formulas for determining die cavity fill time is the NADCA fill time equation by J. F. Wallace and E. A. Herman: the equation takes slightly different forms in different literature. The following equation and parameters are modified from Mike Ward: Gating Manual, NADCA, USA, 2006.

\[
\begin{align*}
t &= K \left( \frac{T_i - T_f + SZ}{T_f - T_d} \right) T \\
\end{align*}
\]

- \( t = \) maximum fill time, s
- \( K = \) empirically derived constant related to the thermal conductivity of the die steel
- \( T = \) characteristic thinnest average wall thickness of the casting, mm
- \( T_f = \) liquidus temperature, °C
- \( T_i = \) metal temperature at the gate, °C
- \( T_d = \) die surface temperature just before the shot, °C
- \( S = \) percent solids at the end of fill, %
- \( Z = \) solids units conversion factor, °C to %, related to the width of the solidification range

The part of the equation between the brackets sets a relation between the consumable heat during the cavity fill time and the temperature difference between the minimum flow temperature and die cavity surface temperature. Constant \( K \) relates this to the die material thermal conductivity and \( T \) to the thinnest wall thicknesses of the casting. More information about this equation can be found in the document ‘Runner and gating systems’.

Constant \( K \) is:

- 0,0312 s / mm between AISI P-20 (pre hardened nitrating plastic mould steel) steel and zinc alloys
- 0,0252 s / mm between AISI H-13 (hot working tool steel alloyed with chromium) and AISI H-21 (hot working tool steel alloyed with chromium and tungsten) steel and magnesium alloys
- 0,0346 s / mm between AISI H-13 and AISI H-21 steels and zinc, aluminum and brass alloys
- 0,0124 s / mm between tungsten and magnesium, zinc, aluminum and brass alloys

Solidified material can be allowed according to the following table.

**Table 1. Recommended percentage of solidified material as a function of the average thinnest wall thickness. If there is a need to have good surface quality in the casting, use lower values. Mike Ward: Gating Manual, NADCA, USA, 2006.**

<table>
<thead>
<tr>
<th>Seinäpaksuus, mm</th>
<th>Suositeltu kiteytyneen aineen määrä (S), %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alumiini</td>
</tr>
<tr>
<td>&lt; 0,8</td>
<td>5</td>
</tr>
<tr>
<td>0,8 - 1,25</td>
<td>5 - 25</td>
</tr>
<tr>
<td>1,25 - 2</td>
<td>15 - 35</td>
</tr>
<tr>
<td>2 - 3</td>
<td>20 - 50</td>
</tr>
</tbody>
</table>

Constant Z is:
- 4.8 °C/% for aluminum alloys ASTM 360, 380 ja 384, all under eutectic, less than 12 % Si containing AlSi(Cu/Mg) alloys
- 5.9 °C/% for aluminum alloy ASTM 390, over eutectic AlSi(Cu/Mg) alloy
- 3.7 °C/% for magnesium alloys
- 3.2 °C/% for zinc alloys 12 and 27
- 2.5 °C/% for zinc alloys 3, 5 and 7
- 4.7 °C/% for brass

Brass HPDC die fill time can be determined by multiplying the wall thickness with a constant:

\[ s < 2 \text{ mm: } t = s \times 7 \]
\[ s = 2 - 3 \text{ mm: } t = s \times 10 \text{ where } t = \text{fill time in ms} \]
\[ s = \text{average minimum wall thickness in mm} \]

Possible casting defects:
If the fill time is too long, some surface defects might occur: non fill, cold flow, swirls, laps, and visible flow lines. Too short fill time does not cause any special defects. It is possible to cut the fill time by raising the plunger speed, but this raises also the gate velocity and this might cause some other problems if the gating is not designed to high velocity.

Gate velocity
Gate velocity has an influence on the casting mechanical properties and on the properties in the casting surface quality. High gate velocity produces higher mechanical properties and lower porosity than lower gate velocity. New HPDC machines are capable of producing gate velocities up to 100 m/s, but the die erosion starts to increase already around 40 m/s. For that reason the higher velocity range from 40 m/s to 100 m/s is not very practical. Gas porosity can be reduced without raising the gate velocity by designing the gate and runner system to maintain smooth, continuous flow profiles and by designing the casting so that no backflow occurs. Backflow can occur if there are shapes on the way of the metal flow (See images 10 - 13).

Possible gate velocity range depends on the selected gate thickness (or vice versa) according to the following formula:

\[ V_g^{1.707} \times T_g \times \rho \geq J \]
where
- \( V_g \) = gate velocity (m/s)
- \( T_g \) = gate thickness (mm)
- \( \rho \) = alloy density (kg/m³)
- \( J \) = constant, 998 000 for aluminum, magnesium and zinc alloys

---


3 Modified to metric dimensioning system from Mike Ward: Gating Manual, NADCA, USA, 2006. 1,707 (or 1 + 1/2) is used as power instead of 1,71 in the original equation.
The formula gives a limit to the lowest recommended gate velocity as a function of the gate thickness. It is not a good practice to choose a low velocity with a thin gate. Typical gate thickness is 0.8 - 3 mm for aluminum alloys, 0.7 – 2.2 mm for magnesium alloys, 0.35 – 1.2 mm for zinc alloys and from 1.5 mm up to 4 mm for brass alloys.

Some examples of gate areas and gate lengths are in the following tables (Table 1 and Table 2). These tables are prepared for total casting and overflow volume of 0.1 dm³. For other volumes multiply the values with the actual volume. For example: if the casting + overflow volume is 0.283 dm³, multiply the table values by 2.83.

After the gate length and thickness approximations there is a need to decide WHERE to place the gate. There are some basic rules even though each casting is different:

- Place thicker sections near the gate and thinner near overflows. This arrangement does not block the metal flow during the solidification shrinkage compensation.
- Avoid two metal fronts to encounter in distance from the gate (See image 4). This is an unwanted situation on the whole, but sometimes not avoidable.
- Frame shaped castings should be gated from inside.
- Try not to place the gate in front of cores. High gate velocity brakes or wears the core rapidly. If there are cores and they can not be removed, see if the gate could be divided into sections between the cores. Consult the foundry and die making company.

Possible casting defects:
Gas and shrinkage porosity are the most common and most trouble causing defects in HPDC. There are contradictory opinions about the causes of gas porosity and the influence of gate velocity to the problem. One reference convinces that the atomized flow phenomena or high gate velocity causes the gas porosity. Another reference recommends using as high gate velocity as possible, even over 50 m/s. It seems that if other variables are the same, raising the gate velocity reduces porosity. But high gate velocity causes excessive die wear. If the gate velocity is too low, this may cause poor flow profile and flow porosity inside the casting. It is worth noting that the gating is designed to some fill time and gate velocity combination and this is the combination the gate works best. Foundry should keep the designed parameters.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Typical ingate velocity</th>
<th>Minimum fill time range for a casting with 1 - 1.25 mm smallest average wall thickness</th>
<th>Gate thickness range for the typical ingate velocities</th>
<th>Gate and vent measures for a cast part with total cavity and overflow volume of 0.1 dm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>17 - 40 m/s</td>
<td>0.016 - 0.038 s</td>
<td>0.8 - 3 mm</td>
<td>Gate area: 65 - 370 mm², Ingate length: 43 - 215 mm, Minimum vent area: 16 - 93 mm², Vent length**: 82 - 460 mm</td>
</tr>
<tr>
<td>Zn</td>
<td>30 - 60 m/s</td>
<td>0.011 - 0.021 s</td>
<td>0.35 - 1.2 mm</td>
<td>Gate area: 80 - 305 mm², Ingate length: 70 - 780 mm, Minimum vent area: 20 - 77 mm², Vent length**: 100 - 380 mm</td>
</tr>
<tr>
<td>Mg</td>
<td>25 - 50 m/s</td>
<td>0.023 - 0.036 s</td>
<td>0.7 - 2.2 mm</td>
<td>Gate area: 55 - 175 mm², Ingate length: 25 - 125 mm, Minimum vent area: 14 - 44 mm², Vent length**: 70 - 220 mm</td>
</tr>
<tr>
<td>Cu (brass)</td>
<td>20 - 50 m/s</td>
<td>0.007 - 0.010 s*</td>
<td>1.5 - 4 mm</td>
<td>Gate area: 200 - 700 mm², Ingate length: 70 - 245 mm, Minimum vent area: 50 - 175 mm², Vent length**: 250 - 875 mm</td>
</tr>
</tbody>
</table>

Casting defects resulting from wrongly selected gate velocity

Table 2. Gate velocity, minimum fill time and gate dimension ranges for different alloy types. Indicative values for 1 – 1,25 mm minimum average wall thickness. Calculated with the presented Wallace and Herman fill time equation.
Table 3. Indicative values for 2 mm minimum average wall thickness. Calculated with the presented Wallace and Herman fill time equation.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Typical ingate velocity</th>
<th>Minimum fill time range for a casting with 2 mm smallest average wall thickness</th>
<th>Gate thickness range for the typical ingate velocities</th>
<th>Gate and vent measures for a cast part with total cavity and overflow volume of 0.1 dm³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Gate area</td>
<td>Ingate length</td>
<td>Minimum vent area</td>
</tr>
<tr>
<td>Al</td>
<td>17 - 40 m/s</td>
<td>0.031 - 0.060 s</td>
<td>0.8 - 3 mm</td>
<td>42 - 190 mm²</td>
</tr>
<tr>
<td>Zn</td>
<td>30 - 60 m/s</td>
<td>0.022 - 0.033 s</td>
<td>0.35 - 1.2 mm</td>
<td>51 - 152 mm²</td>
</tr>
<tr>
<td>Mg</td>
<td>25 - 50 m/s</td>
<td>0.047 - 0.058 s</td>
<td>0.7 - 2.2 mm</td>
<td>34 - 85 mm²</td>
</tr>
<tr>
<td>Cu (brass)</td>
<td>20 - 50 m/s</td>
<td>0.02 s***</td>
<td>1.5 - 4 mm</td>
<td>100 - 250 mm²</td>
</tr>
</tbody>
</table>

Gate and Venting - 8

Table 4. Indicative values for 3 mm minimum average wall thickness. Calculated with the presented Wallace and Herman fill time equation.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Typical ingate velocity</th>
<th>Minimum fill time range for a casting with 3 mm smallest average wall thickness</th>
<th>Gate thickness range for the typical ingate velocities</th>
<th>Gate and vent measures for a cast part with total cavity and overflow volume of 0.1 dm³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Gate area</td>
<td>Ingate length</td>
<td>Minimum vent area</td>
</tr>
<tr>
<td>Al</td>
<td>17 - 40 m/s</td>
<td>0.047 - 0.090 s</td>
<td>0.8 - 3 mm</td>
<td>30 - 125 mm²</td>
</tr>
<tr>
<td>Zn</td>
<td>30 - 60 m/s</td>
<td>0.033 - 0.050 s</td>
<td>0.35 - 1.2 mm</td>
<td>35 - 101 mm²</td>
</tr>
<tr>
<td>Mg</td>
<td>25 - 50 m/s</td>
<td>0.070 - 0.087 s</td>
<td>0.7 - 2.2 mm</td>
<td>23 - 57 mm²</td>
</tr>
<tr>
<td>Cu (brass)</td>
<td>20 - 50 m/s</td>
<td>0.03 s***</td>
<td>1.5 - 4 mm</td>
<td>70 - 167 mm²</td>
</tr>
</tbody>
</table>

* Estimated by calculating with the formula \( t = s \times 7 \).

** Vent thickness 0.2 mm.

*** Estimated by calculating with the formula \( t = s \times 10 \).

Additional information under the title ‘Runner and gating systems’. Die making company and/or foundry calculate the gate area, gate velocity and cavity fill time more precisely. They have many years experience in this topic and it is recommended to rely on their opinion. The tables and equations are only for checking.
3. Division of the casting into gating segments

Gating segment is a portion of the casting where metal flows to a relatively coherent direction. Avoid closed ends: There should always be a vent on the opposite side of the gating segment. Tangential runner gives good possibilities to direct the metal flow. (See images.)

Image 12. A cup shaped casting with narrow rib-type projections in the middle. The metal flow is directed through the flat projections in the sides of the casting – both in upward and sideward directions. The rib-type projections will cause problems.

Image 13. Overflows for the casting.

Image 14. Segmented casting. The rib-shaped projections form closed cavities in the middle segment and make the metal flow more complicated. It is possible that some backflow occurs in the middle segment. Backflow mixes gas to the metal and causes porosity.

Image 15. Modified design. The long rib-shape projections are now smaller. Metal flows better to the right directions and there are no closed shapes.

Foundry and die making company may suggest some modifications to the casting design. Sometimes it is not possible to make these changes. The reasons can be technical or they can be related to the visual appearance of the casting. It is recommended to consult the foundry technical personnel to find a good compromising solution in these cases. Blind cavities are cast able and can be produced in good surface and inner quality with vacuum system or other technical solution.

NOTE: It is the die and gating system designer’s task to divide the casting into segments, but the casting designer should also be aware of this step to be able to make proper designs and take the gate and vent positioning into account.
4. Fill time and gate area calculations by segment; gate velocity selection by segment

3D CAD software gives an excellent possibility to measure casting total volume, volume for each gating segment and the projected area. Total volume and segment volumes are used in fill time calculations. Projected area determines the required locking force in the HPDC machine. The best option is to deliver the native format casting model to the foundry and die making company, but the neutral formats (IGES, STEP and parasolid) are also feasible. If neutral format is chosen it better that the casting designer measures the thinnest average wall thickness.

Example: Fill time, gate area and length

Total casting volume \( V_s \) is 0.0375 dm³ and total overflow volume \( V_o \) 0.0147 dm³. Casting width is 120 mm, length 80 mm and height 45 mm. Average minimum wall thickness is 1.8 mm. Overflow volume is about 40 % of each segment, which should be enough to produce a good surface quality for a casting with 1.8 mm minimum wall thickness. There are totally 5 casting segments and 6 overflows. (See image.)


The casting material is aluminum, AlSi10Mg. The process is cold chamber HPDC. Liquidus temperature of AlSi10Mg alloy is 600 °C and solidus 530 °C. If the casting temperature is 690 °C, temperature at the ingate \( (T_i) \) is around 660 °C. Minimum flow temperature \( (T_f) \) for this alloy is 570 °C and die cavity temperature \( (T_c) \) after a good production start 340°C. Only 15% solids are allowed to obtain a good surface quality. SZ will be then 72 °C. Die cavity materials are some common tool steel. The constant \( K \) is 0.0346 s/mm. With this information minimum fill time \( (t) \) will be:

\[
t = K \left( \frac{T_i - T_c + SZ}{T_f - T_c} \right) = 0.0346 \text{ s/} \text{mm} \left( \frac{660°C - 570°C + 72°C}{570°C - 260°C} \right) 1.8 \text{mm} = 0.0325 \text{s}
\]

Gate thickness \( (h) \) is selected to 1.0 mm, one third of the flange thickness. Gate velocity is selected to 32 m/s, as low as possible not to cause excessive die wear. Minimum velocity at 1.0 mm gate is 32 m/s.

Gate area \( (A) \) is:

\[
A = \frac{Q}{v_g} = \frac{V_s + V_o}{t} = \frac{0.0375 \text{dm}^3 + 0.0147 \text{dm}^3}{0.0325 \text{s}} \left/ \frac{320 \text{dm} / \text{s} = 50.2 \text{mm}^2}{0.0325 \text{s}} \right.
\]

Gate length will be then: \( A / h = 50.2 \). The calculated value was a minimum fill time. It is recommended to use lower values. If the fill time is cut to 70 % of the original value, \( 0.7 \times 0.0325 \text{ s} = 0.0228 \text{ s} \), the gate length will be 71.5 mm. This value is accepted.
The next table presents the fill time, gate area and gate length per casting segment.

### Table 5. Gate length per casting segment

<table>
<thead>
<tr>
<th>Segment</th>
<th>Segment + overflow volume, dm³</th>
<th>Minimum fill time, s</th>
<th>Gate area, mm²</th>
<th>Gate length, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0063</td>
<td>0.0228</td>
<td>8.7</td>
<td>8.7</td>
</tr>
<tr>
<td>2</td>
<td>0.0114</td>
<td>0.0228</td>
<td>15.6</td>
<td>15.6</td>
</tr>
<tr>
<td>3</td>
<td>0.0167</td>
<td>0.0228</td>
<td>22.9</td>
<td>22.9</td>
</tr>
<tr>
<td>4</td>
<td>0.0114</td>
<td>0.0228</td>
<td>15.6</td>
<td>15.6</td>
</tr>
<tr>
<td>5</td>
<td>0.0063</td>
<td>0.0228</td>
<td>8.7</td>
<td>8.7</td>
</tr>
<tr>
<td>Total</td>
<td>0.052</td>
<td>0.0228</td>
<td>71.5</td>
<td>71.5</td>
</tr>
</tbody>
</table>

### 5. PQ² analysis

PQ² analysis matches the selected gate velocity to the HPDC machine plunger hydraulic system. The plunger hydraulics consists of nitrogen bottles, accumulator, computer controlled valve system, and a hydraulic cylinder to which the plunger is attached. The purpose of the plunger hydraulics is to move the plunger and fill the die cavity. (See image)

![Image 17. Cold chamber high pressure die casting machine plunger hydraulics.](image)

Plunger movement has three phases:

- Slow phase during which the runner is filled up to the gate.
- Fast phase during which the cavity and overflows are filled. Fast phase is adjusted to fill the mould cavity in the calculated fill time.
- Intensification phase during which a casting is pressed with a very high pressure.

Gate velocity depends on the metal pressure during the fast shot phase according to the following formula:\(^4\):

\[
P_m = \frac{\rho}{2g} \left( \frac{V_g}{C_d} \right)^2
\]

- \(P_m\) = metal pressure Pa
- \(\rho\) = metal density kg/m³
- \(g\) = gravitational constant m/s²
- \(V_g\) = gate velocity m/s
- \(C_d\) = coefficient of discharge

HPDC machines have unique pressure and velocity profiles. The coefficient of discharge represents the variation between machines. Typical value is 0.45 - 0.5.

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\(^4\) Mike Ward: Gating Manual, NADCA, USA, 2006
HPDC foundries analyze their machines to find out the dependence between the velocity and the pressure inside the plunger hydraulics. $P_m$ is theoretical, actual value can be different.

The HPDC machines are classified by their locking force. Locking force is the force, which resists the mould opening in the end of the shot. When the mould is totally filled, a high pressure forms inside the mould cavity. The pressure is still increased in the third, intensification phase of the shot. These pressures form a force which is proportional to the projected area of the casting. Projected area is the area of the casting in the parting surface direction. (See image.)

Metal pressure creates mold breaking force which is proportional to the projected area with the equation $F = P \times A$. This calculation is used in estimating the required HPDC machine size. For example if the intensification pressure is 550 bar = $550 \times 10^8$ N/m², the projected area of 1,49 dm² creates a die breaking force of 820 kN. This force would require a 82 kilotonne HPDC machine, which is very small. Present HPDC machine size varies from 100 to 1000 kilotonnes.

Consequence of the dependences between the metal pressure and gate velocity and on the other hand the gate velocity and the pressure inside the die cavity is, that it is not always possible to produce wide casting with high gate velocity and/or high end pressure. There is a need to compromise.

6. Modifications and a new tryout

Gating design is compromising. It is done together with HPDC foundry, casting designer and mould designer. It is likely that there will be something to correct after first tryout. There are also many other details than gating to discuss and develop. Notice that designing a castable part may be a time consuming project.
References


W. G. Walkington: Die Casting Defects / Causes and solutions, NADCA, USA, 1997