Manufacturing – Casting methods

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1 Casting methods

1.1 Overview of casting processes and their use in automotive applications

Automotive casting processes can be differentiated according to (A) mould filling and (B) moulding technologies. The following methods are described in this section and are ranked according to current usage in the fig. below:

1) Green sand casting
2) Modified DISAmatic casting
3) Core package casting
4) Gravity die casting
5) Low pressure die casting
6) High pressure die casting
7) Vacuum die casting
8) Squeeze casting
9) Thixocasting
10) Vacuum riserless casting
11) Lost foam casting

Casting methods ordered for casting and moulding technology, size shows market importance

Source: VAW
1.2 Trends in market share of casting methods for engine blocks and heads

**Aluminium engine blocks**

Total production 2000 = 4.5m units  
Total production 2006 = 8.3m units

- CPS - Core package system  
- HPDC - High pressure die casting  
- GDC - Gravity die casting  
- LFC - Lost foam casting  
- LPDC - Low pressure die casting

Source: VAW AP

**Aluminium cylinder heads**

Total production 2000 = 16.5m units  
Total production 2006 = 18.8m units

- CPS - Core package system  
- RC - Rotacast® die casting  
- GDC - Gravity die casting  
- LFC - Lost foam casting  
- LPDC - Low pressure die casting

Source: VAW AP
1.3 Green sand castings

1.3.1 Green sand casting (Horizontal moulding)

The traditional green sand casting process, combined with high-speed moulding lines, is a very flexible process with high productivity for the manufacture of aluminium castings. Automatic pattern-change stations enable complete sets to be changed within the cycle time.

For automotive applications, the process is used to cast:
- Intake manifolds
- Oil pan housings
- Structural parts
- Chassis parts

The photographs show a high-speed horizontal moulding line with typical examples of castings produced using this method.

High-speed horizontal moulding line

Green sand castings
1.3.2 Moulding process

Loose moulding sand is filled into the mould area formed by the pattern plate/pattern bolster, the mould box and the filling frame. Compressed air is then forced through the mould to compact the sand. The air flows through the sand from the back of the mould to the pattern and escapes through vents in the pattern plate. The air flow thus moves the sand into the less accessible regions of the pattern and greatly improves compaction.

The final strength in the mould is achieved in a subsequent pressing stage by means of a fixed or flexible pressure plate, a water cushion or a multi-platen press. The pressure of the press, as well as the pressure and duration of the air flow, can be controlled. This enables optimum mould strengths tailored to the needs of the individual application.
1.3.3 DISAmatic casting

Automated green sand casting: DISAmatic, AGSC

Automated green sand casting offers a reasonable alternative to conventional die casting processes (high pressure / low pressure / vacuum-assisted or not). This holds for middle and high volume series, especially for automotive applications.

Manufacturing in high pressure die casting is limited by wall-thickness and design. I.e. producing a complicated inner structure by using lost cores is still not economically feasible in this process. Low pressure die casting's productivity is limited by solidification time, leading to cycle times of typically several minutes. Automated green sand casting has no such limits.

The original DISAmatic process was advanced by Alcoa for manufacturing of high-quality automotive castings. Alcoa's variant green sand casting is AGSC (Alcoa Green Sand Casting).

Examples of AGSC castings
From left: Heat Exchanger, Hat Profile, Brake Calipers, Knuckles
Source: Alcoa
DISAmatic casting

The DISAmatic casting process is a container-less sand casting process. The mold is divided upright. Front and rear mold half are formed by the shaped faces of every sand block. Stacked on a conveyor belt, the pouring cavity is between two blocks each.

Insertion of individual cores or whole core packets is possible and can be carried out in an automated manner. The finished molds are pushed forward when a new sand block is added.

The existing plant can produce and fill up to 200 sand molds per hour. Other machines of this type can produce up to 420 molds per hour. By using multiple cavities for smaller parts an hourly output surpassing all other casting processes is achievable.

The process was modified in particular with regard to form filling to ensure high-quality castings with excellent microstructure.

AGSC molds on conveyor belt

Source: Alcoa
Influence of mold filling rate

For a clean microstructure it is necessary to ensure non-turbulent mold filling in addition to using clean metal. The purification of the metal is implemented by permanent degassing and the use of filters. In order to prevent impurities during mold filling (in particular oxide inclusions), attention has to be paid to a uniform filling rate. If the mold filling rate exceeds a critical value, separation of metal drops or folding of the metal front occurs, leading to formation of additional oxides (see figures).

Above: Separation of metal drops and folding of metal surface
Below: If critical velocity is exceeded, metal drops separate
Source: Alcoa

The critical velocity of the melt $v$ is determined by the balance between inner pressure and the surface tension which is formed by the specific surface energy $\delta$ and the radius of curvature of the surface $r$:

- Inner pressure $= \rho \cdot v^2$
- Surface tension $= 2 \delta / r$

$$\Rightarrow \text{Critical velocity} = \left(2 \frac{\delta}{(r \cdot \rho)}\right)^{0.5}$$

For molten aluminum, the critical velocity is around 500 mm/s.

In the case of gravity casting, a height of only 13 mm is sufficient to reach this speed. Model investigations on test plates by the University of Birmingham confirmed this result. The figure on the right shows the occurrence of oxide films and the bending strength in dependence of the velocity of filling for plates of 5 mm and 10 mm thickness, respectively. If the velocity of filling exceeds 500 mm/s oxides causing cracks are observed more frequently and the bending strength of the plates is dramatically reduced.
Influence of Velocity of Filling on Oxide Formation and Bending Strength

Source: Alcoa
Mould filling by an electro-magnetic pump

The consideration of the drop height makes using force of gravity for mold filling undesirable. Rather, an electro-magnetic pump is chosen which allows feeding fluid metal with a controlled rate. In this case, the mold filling does not require a constant mass flow over time but the pumping rate has to be adapted to the geometry of the part.

The figure below shows anti-gravity mold filling with an electro-magnetic pump used in the AGSC process.

Mold filling from below by means of an electro-magnetic pump

Source: Alcoa
Wendy system

The figure below shows the mold filling rate for gravity and electro-magnetic pump in a schematic comparison. The so-called Wendy system (second figure) is used for the evaluation of the correct mass flow over time. Via detectors in a mold, the raising level of metal in the mold is recorded continuously.

Comparison of Mold Filling by Gravitation vs. Electro-magnetic Pump

The Pump Allows a Tailored Filling Curve

Source: Alcoa

Deviations from the planned filling curve lead to a patched curve (by means of a computer) for pump power over filling time. The optimum control curve is calculated in an iterative process. This curve is then used in the later production of the respective part in order to control the mold filling.
AGSC characteristics leading to cost reductions

Process characteristics of a DISAmatic machine type 2120 (as of 2002, other types are available):
Plate size: 850 mm x 650 mm, usable area: 700 mm x 550 mm. The maximum form height is 378 mm. The maximum part weight is 30 kg. The minimum wall thickness is 3 mm.

Overview of the AGSC Process: Complete Control of Mold Filling Combined With High Productivity
Source: Alcoa

While there is no hard upper limit for wall thickness the process works best for wall thickness of up to approx. 35 mm. Over 35 mm, the advantages of the bigger mold area are minimised e.g. by bigger risers.
The use of sand as a mold medium allows a high degree of freedom for design of high-volume parts. Since the tools only have contact with molding sand, wear is almost nonexistent. Therefore, the life of tools is a multiple of the life of ingot molds and die casting tools (approx. one million shots). This means that even for high volume parts, investments for replacement tools can be omitted frequently. In addition the tool costs are - compared to ingot molds and dies for die casting - smaller. The tool changing times are short, less than 10 minutes. All this reduces costs significantly.
Plastic tools for prototypes are possible. This means that prototypes can be produced in the final casting process - effectively speeding up the introduction of new products.
Properties of castings

Today (2001), the main alloy in production in AGSC is A356 (AlSi7Mg) in tempers -T6 and -T7. AGSC castings are weldable and heat treatable. The process makes it possible to keep very narrow tolerances. Parts which are inserted in vehicles are characterized by uncritical behaviour in crash.

The figure below shows a bumper bracket (A356-T7) connecting the crash boxes of the Mercedes A-Class to the Längsträger. The controlled mold filling of AGSC leads to a very clean and dense microstructure.

![AGSC Bumper Bracket (A356-T7)](image)

The wall-thickness of this crash-relevant part varies between 3 mm and 6 mm

Source: Alcoa

Numerous (>500) tensile tests (section is 4.1 mm thick) lead to the following results for the bumper bracket:

Typical (average) TYE: 199MPa, 144MPa, 11%
95%-99% minimum TYE: 177MPa, 125MPa, 7%
95%-90% minimum TYE: 188MPa, 136MPa, 9%

Explanation of mechanical properties:
TYE means three values from tensile tests: Ultimate Tensile Strength, Yield Strength (Rp0.2) and Elongation.

Typical properties are average values and have no statistical assurance.

95-99% minimum properties: 0.99 of the population of values is expected to be equal to or greater than this property value with 95% confidence.

95-90% minimum properties: 0.90 of the population of values is expected to be equal to or greater than this property value with 95% confidence.

In addition to very good mean values for elongation the standard deviations are small, demonstrating high stability of the process. The figure below compares AGSC with conventional sand casting.
Comparison: Distribution of Rm, conventional sand casting vs. AGSC, schematically

Source: Alcoa

Cast suspension parts showed the following TYE values in T6: 271.3 MPa, 211 MPa, 8 %.
(29 samples, thickness of sections 4-16 mm.)

AGSC has demonstrated its suitability especially for automotive parts but also complex geometries like heat exchangers. Other examples: Gear parts, knuckles, wheels, calipers, guidance cases but also shock towers. Safety parts in particular gain by the high quality microstructure.
AGSC – Product examples

The pictures show examples of parts demonstrating design possibilities and productivity.

Tunnel: Size 400 x 300 x 180 mm³, wall thickness 3 mm, weight 0.9 kg
Source: Alcoa

Tunnel: Size 400 x 300 x 180 mm³, wall thickness 3 mm, weight 0.9 kg
Source: Alcoa

Shock Tower: Size 450 x 400 x 250 mm³, wall thickness 3 mm, weight 3 kg
Source: Alcoa
Shock Tower: Size 450 x 400 x 250 mm³, wall thickness 3 mm, weight 3 kg
Source: Alcoa

Rotor, high volume possible: up to 2800 parts per hour
Source: Alcoa

Brake Caliper, high volume possible: up to 1200 parts per hour
Source: Alcoa

Casing, high volume possible: up to 1200 parts per hour
Source: Alcoa
1.4 Core package casting

1.4.1 Introduction

See also:
- AAM – Applications – 1 Power train > Engine > Cylinder block

Literature:
- Smetan, H.: Kernpaketverfahren im Aluminiummotorenguss, MTZ 61, 2000, No.10, P.712-715

The core package casting process, where the entire sand mould consists of single sand cores, was industrially applied first in 1970 using low pressure filling by means of an electromagnetic pump. Due to low productivity, the process was restricted to low volume series. However, the increasing interest in the outstanding dimensional quality and possible complexity of the castings led to further developments and thus, (e.g.) the Core Package System (CPS®) has become an established casting process for the volume production of engine blocks within a short period of time.

In the following screens, the process and design features of the core package casting process are described:
- Design features
- Core manufacturing
- Mould filling
- Roll-over and solidification
- Process features

Core package for V6 engine block
Source: VAW
Partly assembled core package for a 4-cylinder engine block
Source: VAW

4-cylinder engine block produced with the CPS® process
1.4.2 Design features

The question, which casting process is optimal for a given product, depends, beside other factors, on the desired complexity of the casting. Like all precision sand casting processes, the core package casting process offers almost unlimited possibilities for product design, e.g. for engine block castings:

- Complicated oil galleries and pre-cast oil channels to feed the crankshaft bearings.
- Complex exhaust gas return systems.
- Secondary air ducts.
- 1 mm thick cooling water passages between the cylinders (facilitated by micro-core technology).
- Casting-in of cylinder liners.

Hang-on and functional parts, such as thermostat housing, oil filter flange and splash wall can be integrated into the engine block with the core package process. Furthermore, the process provides extensive design freedom, for example in the design of undercuts, to reduce weight through the use of additional cores and/ or cavities and curved ports.

Different designs for oil gallery cores
Source: VAW

Example of a complex oil gallery core design
Source: VAW
Schematic diagram showing the economic relationship between complexity, production volume and casting process.

Sources: VAW
1.4.3 Process description – Core manufacturing

See also:
- AAM – Applications – 1 Power train > Engine > Cylinder block

This process applies entirely resin bonded sand cores. Specifically, silica sand is used in the polyurethane cold-box process. The core package comprises also the whole running and feeding system. The core packages are, to a large extent, assembled automatically. Production lines with a capacity of up to 160 core packages per hour are currently in operation. Extremely tight tolerances are achievable, so that e.g. grey iron liners can be placed into the core package with a position tolerance of ±0.3 mm. Usually, the core packages are stored in a buffer and then fed into the casting line.

Inserted parts such as grey iron liners can be preheated by induction coils in their final position in the core package prior to mould filling. This guarantees reproducible and repeatable conditions concerning the contact between the grey iron liners and the aluminium cast alloy.
Manual assembly of core packages for engine block castings

Source: VAW
1.4.4 Process description – Mould filling

See also:
   AAM – Applications – 1 Power train > Engine > Cylinder block

Core packages from the buffer are flushed with inert gas and continuously fed into the casting line, allowing one casting every 20 seconds. This requires a continuous metal supply which is realised by means of a launder with a casting nozzle and a stopper rod.

After an optional inductive pre-heating of grey iron liners, the core package is connected to the nozzle and the filling process is started by raising the stopper. The mould filling takes place through the feeder, which (only during filling) is located underneath the casting. The signal to stop mould filling is given by a control laser which detects the actual metal level.

Process steps 1 to 4 "filling the mould" of the CPS process
Source: VAW AG
1.4.5 Process description – Roll-over and solidification

Roll-over - Shortly after disconnecting from the metal supply position, the core package is rotated into the solidification position with the feeders now being on top of the casting.

Rotating of the core package into the solidification position
Source: VAW

Solidification - The coldest metal which entered the mould first is now in a bottom position being in the greatest distance to the hot feeder and solidifies first. Hence, an optimal quasi-directional solidification towards the feeder takes place. However, due to the fact that, during filling the feeder necks are acting as gating, a compromise to find the best possible cross sections has to be made, to achieve both, a smooth filling and an optimal feeding.

Quasi-directional solidification
Source: VAW
Heat treatment - The core packages containing just solidified but still hot castings inside can be directly transferred into a heat treatment furnace, where they are de-cored and solution heat treated simultaneously in a very energy effective manner.
1.4.6 Process description – Process features

See also:
- AAM – Applications – 1 Power train > Engine > Cylinder block > Requirements for aluminium cylinder blocks

Literature:

There are two principal ways to place an engine block into the core package:

1. Filling and feeding via the oil pan flange and optional additionally via the main bearing saddles. In this case, a chill cooling may be applied on the joint face providing an optimised directional solidification and a fine microstructure in the chilled area. This in turn, improves the mechanical properties in terms of elongation and tensile strength.

2. Filling and feeding via the joint face with optional chill cooling on the main bearing saddles. This configuration is chosen, when good static and dynamic strength is required in the main bearings.

![Diagram](image.png)

Version 1: Filling and feeding via oil pan flange, chill cooling on joint face

Source: VAW
Version 2: Filling and feeding via joint face, chill cooling on main bearing saddles

Source: VAW

The dendritic microstructure of a casting influences its mechanical properties and is strongly depending on the cooling rate in the considered area. The distance between secondary dendrite arms (DAS) depends on the local solidification time and is therefore a means to check the cooling conditions, s. fig. below.

Dendrite arm spacings depending on chill position (feeding from the opposite side)

Source: VAW
1.5 Gravity die casting

1.5.1 Characteristics of process

Gravity die casting is one of the standard processes for the manufacture of high-integrity automotive castings. It represents proven and absolute precision technology for the production of large batch quantities. This process is used in carousel casting units or in shuttle technique particularly for the manufacture of engine castings.

Optimum heat dissipation from the solidifying casting through the die leads to short solidification times. This results in castings which have good mechanical properties, especially after an additional heat treatment.

In addition to producing ever more complicated cylinder heads for petrol and diesel engines, gravity die casting is also used for the manufacture of diesel engine blocks with cast-in grey iron liners.
1.5.2 Process description

In gravity die casting processes, the melt is metallurgically treated in the holding furnace, which is positioned near the dies.

The quantity of melt for one casting is transported in a ladle and poured into the riser system of the mould by tilting the ladle. The melt fills the mould cavity smoothly from the bottom up until it appears in the risers positioned above the casting.

In the example shown, i.e. the casting of a cylinder head, the mould filling and solidification conditions can be influenced by the design of the gating system and the risers in the top core. Directional solidification can be forced by using water cooling in the bottom of the die (combustion chamber area of the head).
1.5.3 Rotacast®

Rotacast® is a new type of casting process*) based on permanent mould casting. This process meets the most exacting requirements and has now been introduced for the volume production of cylinder heads.

Rotacast® procedure: cores are inserted in the mould, the die is closed and rotated 180° around its long axis. In this way, the combustion chamber of the die cavity shoots upwards. In the top core, the gating system comprises the whole length of the cylinder head. A tundish, which is filled with molten metal and connected firmly to the die, docks tightly with the top core from below. To fill the die with melt, the die and tundish are rotated together around the long axis in a numerically controlled process. This ensures that the metal fills the die cavity smoothly in laminar flow. Due to the large gating cross-section, high filling speeds are avoided. The die cavity is thus filled free of turbulence.

*) developed by VAW aluminium AG

The gating system can be laid out in the top core in accordance with the respective geometry of the casting. Changes can also be made relatively easily. The venting of the die cavity and the escape of the core gases take place via the melt-free passages in the top core directly into the tundish or via the die joint and core prints.

Through laminar flow die filling, local overheating due to so-called "channelling effects" – preferred flow path taken by the melt – is prevented.

The melt flows from the tundish into the die cavity and reaches its final solidification position via the shortest route.

The solidification process already begins on the bottom plate during die filling – very high cooling rates are achieved – and slows in the area of the core-sand riser. The efficiency of the riser is improved when it is subsequently filled with hot melt directly from the tundish. Similarly, the build-up of less overpressure in the tundish after reaching the solidification position also has positive effects.

With Rotacast® die casting, die filling and solidification can be optimally directed and customised material properties achieved.

Rotacast® castings display a very fine-grained cast structure with low porosity, especially in the combustion chamber area of cylinder heads. They offer great potential for the manufacture of "tailored castings" with the aid of well-devised die cooling technology, optimised alloys and subsequent heat treatment.
Production line Rotacast®: closed die with inserted cores before rotation into casting position.
1.6 Low pressure die casting

1.6.1 LPDC description and product examples

Low pressure die casting is a well-known casting process, especially for aluminium wheels in passenger cars. The process is also used in the production of big V-engine blocks in hypereutectic aluminium alloys and in the casting of air-cooled cylinder heads for motorcycles. Mould filling is controlled by regulating the pressure in the casting furnace. The melt flows through the riser tube which is positioned under the melt surface of the furnace and fills the mould very smoothly with clean melt from the bottom up. After mould filling, solidification starts from the opposite end of the mould in the direction of the tube. By increasing the pressure in the casting furnace, good feeding is guaranteed. Cycle times are long due to the fact that the casting is connected to the big melt volume by the riser tube during solidification.
LPDC cast "BBS Challenge" wheel

LPDC cast V-8 cylinder block
1.6.2 LPDC machine

With active water or air-cooling channels in the mould, the thermal conditions can be influenced during solidification.

Directional solidification and increased pressure lead to small riser volumes. This effect can be seen in the pictures of the two wheels below:

- **Top** - Low pressure die casting
- **Bottom** - Gravity die casting

![LPDC wheel as cast, note small riser at hub center](source: VAW)

![Gravity Die Cast wheel, note large risers at rim and center hub](source: VAW)

The casting unit of a low-pressure machine consists of a pressure-tight holding furnace, the pressure control unit, the hydraulic die manipulators and usually one die for the casting.

![LPDC casting machine and furnace](source: Kutz)
1.7 High pressure die castings

1.7.1 The HPDC process

- Filling speed and intensification pressure differentiates high-pressure die casting from most other casting processes.
- After liquid metal is transferred to the shot sleeve (s. fig. below), the plunger slowly closes to shut-off the filling port.

![Schematic drawing of a typical cold-chamber diecasting machine](image)

This is the only HPDC-type used with aluminium

- The plunger is then moved towards the die at a controlled but high speed in order to fill the die cavity.
- With the potential for highly automated operation, the high-pressure die casting (HPDC) process is capable of extremely high levels of productivity.
- HPDC machines are size rated by the closing force (s. figs.)

![Photograph of a fairly common 600 ton (5400kN) diecast machine](image)

Source: IdraPrince

HPDC machines:
5.4 MN (above),
35 MN (below).
This 4000 ton (35MN) machine is close to the upper end of available size ranges
Source: IdraPrince
1.7.2 HPDC process cycle

Process cycle (s. schemes below):
1.7.3 Typical automotive applications of aluminium High Pressure Die Castings

Transmission cases are one of the largest automotive parts commonly diecast

The common size range and close tolerances have been used to good effect in defining the hydraulic network in large transmission cases shown above. The Belt Tensioners (below) are typical of small die cast parts:

Roughly 200g in weight, these belt tensioners are amongst the smaller automotive die castings

Productivity for small parts like this is usually enhanced via multi-cavity die designs, e.g. 4 to 8 cavities per die. Production rates are up to 100 parts per hour per cavity.

To be die cast, engine blocks must designed with an open deck
Cast-in and mechanically locked steel inserts such as those in this engine block skirt are easy when die cast.
1.7.4 Design considerations

Low magnification view of a section through a typical die cast part

Physical design considerations:
- Only straight steel core pulls can be used to define internal passages.
- Core pulls increase tooling costs.
- Sand coring is generally not possible.
- Inserts can frequently be cast into the part. Hollow tubes, threaded inserts to fill out bosses, engine bore liners, and wear resistant inserts are common.
- Feeding of shrinkage is via the gates alone; parts should be designed with as uniform a thickness as possible.

Metallurgical design considerations:
- Part ductility is limited by process considerations to ~3% on average.
- Die castings should not be used for load bearing safety critical parts.
- Die castings are not heat treatable.
- Die casting are generally produced using secondary (recycled) alloys; this reduces cost.
- Fatigue properties of die castings are good so long as the very smooth as-cast surface is not machined away.

Macrostructure:
Die castings exhibit three regions internally:
- The surface skin – dense and fine. The skin gives die castings good fatigue life. It should not be machined away unless absolutely necessary.
- The interior body of the casting – sound metal.
- The core – at the centre of the part, the core is usually porous. It may not be present in high quality parts. It is harmless in many applications. Core porosity may be a combination of entrained air and shrinkage.
1.7.5 Common and special purpose HPDC alloys

**Al18Si (AA 391) Hypereutectic, Parent Alloy, 2-Stroke Engine Bore**

Source: Mercury Marine Ltd.

Macro section showing entrained air frozen into a high pressure die cast part

**Entrained Air** makes HPDC parts non-heat treatable. Air bubbles entrapped under high pressure during solidification will cause HPDC parts to **blisters** during solutionising.

**Common Al Die casting Alloys:**

**AlSi8Cu3 (AA 380)**

- Rp0.2% = 160 MPa, Rm = 325 MPa, A5 = 0.5-3%

**AlSi10Cu (AA 383)**

- Rp0.2% = 150 MPa, Rm = 310 MPa, A5 = 1-3%

- These are the most common alloys in use for general-purpose die castings.
- General utility castings, transmission cases, blocks etc.

**Caution:** HPDC Properties are very process/part dependent; only typical as-cast values are shown.
Al18Si (AA 391) Alloy Microstructure - Primary Si Imparts Wear Resistance

Source: Mercury Marine Ltd.

Typical AlSi8Cu (AA 380 microstructure), Hypoeutectic Al-Si plus Fe phases

Special Purpose Al Die casting Alloys

**AlSi5 (AA C443)**
Rp0.2%=110 MPa, Rm =230 MPa, A5=9%
Where exceptional ductility at moderate strength is required. Increased corrosion resistance (low Cu). (eg. steering wheels)

**AlSi12 (AA 413)**
Rp0.2%=140 MPa, Rm =300 MPa, A5=0.5-2%
For intricate thin castings.

**AlSi17Cu4Mg (AA 390)**
Rp0.2%=240 MPa, Rm=280 MPa, A5=1%
A hypereutectic wear-resistant alloy. Used for parent bore engine blocks, compressor parts, pulleys, brake shoes.
1.8 Vacuum die castings

1.8.1 Characteristics of VDC

Aluminium-intensive cars like Audi A2, Audi A8 or Ferrari Modena rely heavily on Vacuum Die Casting (VDC) for the space frame design. VDC has several characteristics that make it highly attractive for automotive applications:

- Thin walls in large structures: Designs using a minimum wall thickness well below 2 mm.
- Joining with standard welding techniques as well as Laser welding and self-piercing rivets.
- Crash worthy structures (i.e. A-pillar of Audi A2, frame Ferrari Modena)
- Wide selection of alloys including heat treatable and non-heat treatable alloys.
- High productivity.

![Space Frame of Ferrari 360 Modena using large VDC shock towers](source)

Source: Alcoa

![Müller-Weingarten vacuum die caster, closing force: 4400 metric tons](source)

Source: Alcoa
1.8.2 VDC Process

Vacuum Dies
The principle of vacuum die casting requires the dies to be very tight. Residual pressure is as low as 20 - 30 hPa. (Normal atmospheric pressure is 1013 hPa). Therefore tools consist of frames and one or several inserts with air seals in between. Good quality tools loose less than 1.5 hPa/s of vacuum.

Melt
The melt is kept in the dosage furnace below the filling chamber. Melt cleanliness determines heat treatability as well as weldability of castings. If the gas content is too high, heat treatment produces humps on the surface, also called blisters.

Vacuum Die Casting Step 1: Dosage
In this step the low air pressure in the filling chamber sucks a portion of melt into the filling chamber. The amount of metal can be adjusted.

1. Step: Dosage, suction of metal into the feeding chamber
Source: Müller-Weingarten

2. Metal Transport:
The piston drives up and seals the suction pipe. The melt is pressed to the gate. Metal velocity in this phase is low.

2. Step: Transport of metal to the gate
Source: Müller-Weingarten
3. Injection:
After the vacuum valves are closed the melt is injected into the die at high rate. During the "shot", metal velocity is high.

4. Post injection densification:
After injection the piston exerts high pressure (> 150 bar) until complete solidification. This leads to a dense microstructure.

Process Control:
Modern die casters allow controlling and documenting up to 40 parameters per shot. This allows precise control and high reproducibility.
Shot control using defined parameters

Source: Alcoa

1: Müller-Weingarten Vacuum Die Casting machine, closing force 4400 metric tons

Source: Alcoa Soest, Germany

2: The opened mold is sprayed with mold release agent by a robot

Source: Alcoa
3: After the mold is closed, the piston injects liquid aluminium into the mould (Shot)
   Source: Alcoa

4: Part is ejected and removed by another robot.
   Source: Alcoa

5: Water quench right after removal (air quench is also possible)
   Source: Alcoa
6: Part is now cool and ready for further processing: deburring, heat treatment, machining etc.

Source: Alcoa
1.8.3 Examples of VDC parts

Ferrari Modena Spaceframe: light colored nodes are produced in AVDC
Source: Alcoa

A-Post
Source: Alcoa

B-Post DC S-Class Coupe
Source: Alcoa
Shock tower Audi A8
Source: Alcoa

A8 Lower A-Post Audi A8
Source: Alcoa
1.8.4 Vacuum Die Casting product examples

**AUDI A2 Space Frame**

- Red: Die casting parts from ALCAN-BDW, Alloy AURAL-2® - High-Q-Cast *
- Blue: Profiles
- Green: Panels

Audi A2 Space Frame: colours indicate different processes

**AUDI A2: High-Q-Cast “B-pillar”**

- Length: 1220 mm
- Wall thickness: 2 mm
- Weight: 2300 g
- Alloy AURAL-2®
- MIG and laser welded

Audi A2: High-Q-Cast "B-pillar"

**Assembly from the front area of AUDI A2 Space Frame**

Assembly from the front area of Audi A2 Space Frame
1.8.5 Mechanical properties

*The table gives typical and minimum mechanical properties for two alloys in production in Alcoa’s plant in Soest, Germany.

AlMg$_3$Mn is a non-heat treatable alloy with ca. 3.5 % Magnesium and 1.3 % Manganese. This alloy is based on solid-solution strengthening, hence no heat treatment required.

AlSi$_9$Mg is a heat treatable alloy with ca. 10 % Silicon and 0.2 % Magnesium. This alloy is precipitate-hardened (Mg$_2$Si) and requires a heat treatment of solid solution, subsequent quenching and ageing.

Both alloys are low on Iron and Copper.

<table>
<thead>
<tr>
<th>Chemical Designation</th>
<th>C 448 T7 Heat treated</th>
<th>C 448 Non heat-treatable</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlSi9Mg</td>
<td>180 / 200</td>
<td>190 / 250</td>
</tr>
<tr>
<td>AlMg3Mn</td>
<td>120 / 140</td>
<td>120 / 150</td>
</tr>
<tr>
<td>Ultimate Strength (min / typ) [MPa]</td>
<td>10 / 15</td>
<td>10 / 20</td>
</tr>
<tr>
<td>Elongation (min / typ) [%]</td>
<td>&gt; 100</td>
<td>&gt; 120</td>
</tr>
<tr>
<td>Weldability</td>
<td>WIG / MIG / Laser</td>
<td>WIG / MIG / Laser</td>
</tr>
<tr>
<td>Self Piercing Riveting</td>
<td>Very good</td>
<td>Very good</td>
</tr>
<tr>
<td>Resistance to Corrosion</td>
<td>resistant</td>
<td>Relatively resistant</td>
</tr>
<tr>
<td>Formability</td>
<td>Very good</td>
<td>Very good</td>
</tr>
<tr>
<td>Surface quality</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Castability</td>
<td>Very good</td>
<td>Design changes necessary</td>
</tr>
</tbody>
</table>

Source: Alcoa
1.9 Squeeze castings

1.9.1 Squeeze Casting – Characteristics

What is Squeeze casting?

This technique was initially similar to forging, with a mould made of a hollow lower dye and an upper dye used as a stamp, which are set on a drop forging press. And the press is started as soon as the liquid metal is poured in the lower dye.

This method is no more widely used, if ever, as 2 problems rise: the thickness of the cast part depends on the quantity of metal poured; and parts must be of rather uniform thickness, unless thinner areas, which solidify before thicker ones, will prevent pressure from applying any more on areas subject to shrinkage.

As a matter of fact, "squeeze-casting", which is then sometimes said "indirect" SC, is now commonly an evolution of pressure die casting, using the same machines, with differences only on the injection speed and on the design of the pouring system:

- the speed of the metal is drastically lowered, so as to avoid any turbulence – typically 0.5 m/s, against 30 to 60 m/s in HPDC – ;
- the solidification must be progressive from the thinner area of the cast part to the biscuit.

In other words the channels must be thicker than the cast part, and the gates set so as to feed any area.

The high cooling speed and the pressure applied give the parts excellent mechanical properties, and squeeze casting is therefore particularly suitable for suspension parts.
1.9.2 UBE squeeze-casting machines and particular tilting-docking shot unit

The "indirect" squeeze casting technique is widely used in the USA and, above all, in Japan, where the machine maker UBE has developed a particular technique of tilting sleeve, using either vertical or horizontal presses.
1.10 Thixocastings

1.10.1 Semi-solid forming

A process at the border between casting and forming

This process makes use of the thixotropic behaviour of semi-solid metallic alloys. Under some conditions the metal behaves like a solid (high viscosity) if not sheared. As soon as shearing occurs, viscosity decreases by orders of magnitude. Under some conditions this effect is reversible.

\[\text{Viscosity resp. Shear rate} vs. \text{Time}\]

Source: JP Gabathuler, Alcan

Metallic alloys have strong thixotropic behaviour if:
\[\begin{align*}
\text{it is possible to bring the metal homogeneously to the required semi-solid state, i.e. enough solidification range is present,} \\
\text{a microstructure with very fine and round grains exists.}
\end{align*}\]

Source: JP Gabathuler, Alcan
Main processes used today in production

All semi-solid forming processes are characterised by:
- 10 to 70% solid phase during forming,
- Thixotropic properties: initially the metal's viscosity is high. After being sheared its viscosity decreases strongly.
- the metal solidifies during forming.

Specific properties of the products:
- Since only part of the metal is liquid, shrinkage porosity is reduced.
- Solidification takes place very rapidly and little heat extraction is necessary.
- Since the viscosity of the metal is high, mould filling occurs in a very laminar way.
- Net-shape parts can be produced.

Thixocasting: Liquid metal is first DC-cast to fine grained billets which are then reheated to the semi-solid state and formed to the final product. This process has been mainly used during the last 20 years.
**Rheocasting**: Liquid metal is directly cooled down to the semi-solid state and processed to the final product. Since 1999, this process family is gaining new attention.

![Process steps of Rheocasting](image)

*Source: Alcan*
Metallurgical aspects of semi-solid processes

**Thixocasting**
The metal used has to show very fine and spherical grains to increase the shear thinning effect during forming.

- DC-casting is normally combined with strong electromagnetic stirring. This leads to fine rosette like grains (fig. below),

![Microstructure of AlSi7Mg0.3 before re-heating](source: Alcan)

- During re-heating the metal, grains become spherical, as required for semi-solid forming (fig. below),

![Microstructure of AlSi7Mg0.3 after re-heating](source: Alcan)

During forming, the weak bridges between the grains break, leading to a strong reduction of viscosity (shear thinning).

**Rheocasting**
During cooling the liquid to the semi-solid state, some specific conditions have to be fulfilled to get the fine grains required.

- A very high amount of grain seeds have to be built. This can be produced by using chemical grain refiners, suitable thermal conditions or mechanical vibrations in the melt,
- During the process of partial solidification, the many grain seeds grow and, after touching their neighbours, get spherical (fig. below).
Microstructure of AlSiMg0.3 alloy ready for forming

Source: Alcan
1.10.2 Suitable alloys and their mechanical properties

Requirements for alloys suitable for semi-solid forming:
- The metal can be brought homogeneously to a liquid fraction between 40 and 60% (i.e. no pure metal or eutectic alloy),
- The solid phase is prone to build a fine globular structure,
- The flow behaviour of the alloy is good.

Static mechanical properties of AlSi7Mg0.3 (most used aluminium alloy) in various temper conditions

Source: Alcan

Fatigue properties of thixoforming samples, A356, T6-temper (R=-1)
1.10.3 Examples of parts produced for the automotive industry using semi-solid forming processes

Examples of parts which have already been in production

- Master brake cylinder
- Wheels
- Fuel rails
Examples of parts which are today in development

From left to right: steering knuckle, injection pump, space frame note
1.10.4 Main process parameters of semi-solid forming and their influence on quality

Casting speed
It is important that the metal front stays together during mould filling. A too high speed can lead to turbulences and air entrapment. At too low speed mould filling could be incomplete.

Geometry of the runner system
Due to the fact that metal is already partly solid, thicker cross sections and short runners are necessary in comparison to die casting. Numerical simulation is a very valuable tool for designing runner systems.

Die temperature
To avoid cold shots, die temperature has to be high enough. Very often, die temperatures of 200 - 250°C lead to good results.

Die parting agent
- Main requirements on mould release agent are:
  - Good separation between mould and metal;
  - Good wetting and adhesion on the mould;
  - Low gas production in contact with metal;
  - Low build up on mould.

Die venting
The air in the mould cavity has to be evacuated during mould filling. This is achieved by venting slots positioned at places which are filled last. These slots should not be thicker than 0.2 mm.

Final metal pressure
Due to the partly solid metal, the risk of shrinkage porosity or hot tears is limited. To avoid it completely, a high final pressure of 500 to 1500 bars is often necessary.
### 1.10.5 Possible defects and ways to avoid them

<table>
<thead>
<tr>
<th>Defect</th>
<th>Non-fills and cold shuts</th>
<th>Gas porosity and blisters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible main cause for defects</td>
<td>Solid fraction too high; mould filling speed too low; mould too cold.</td>
<td>Turbulent mould filling; runner’s geometry not adequate; not enough venting; water in mould; die parting agent produces gases.</td>
</tr>
<tr>
<td>Way to avoid defects</td>
<td>Increase liquid fraction; increase speed; heat mould more.</td>
<td>Use smooth runners with cylindrical cross sections. If necessary, use vacuum.</td>
</tr>
</tbody>
</table>

**Examples**

- **Non-fills**
  - Source: EFU

- **Gas porosity and blisters**
  - Source: Alcan

<table>
<thead>
<tr>
<th>Defect</th>
<th>Inclusions (mainly oxides)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible main cause for defects</td>
<td>Retention system for oxide skin of metal not efficient enough; two metal fronts hit together.</td>
</tr>
<tr>
<td>Way to avoid defects</td>
<td>Use and optimise oxide retention systems; fronts with oxides should be brought into overflows.</td>
</tr>
</tbody>
</table>

**Examples**

- **Inclusions**
  - Source: Alcan

<table>
<thead>
<tr>
<th>Defect</th>
<th>Shrinkage porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible main cause for defects</td>
<td>Feeding of large cross sections is not good enough.</td>
</tr>
<tr>
<td>Way to avoid defects</td>
<td>Dimension runner and gating systems for good feeding; use numerical simulation to control and optimise them.</td>
</tr>
</tbody>
</table>
Examples

Shrinkage porosity
Source: EFU

Defect
Possible main cause for defects
Geometry of channels, high flow velocities can lead to separations between solid and liquid phases.

Way to avoid defects
Increase mould filling speed gives often good results; improve channel's geometry (smoother flow path).

Examples

Segregations
Source: Alcan
1.11 Vacuum riserless castings

1.11.1 VRC / PRC – Introduction

VRC / PRC is a combination of Vacuum Riserless Casting (VRC) with Pressure Riserless Casting (PRC) (fig.1). This variant of low pressure die casting has been developed by Alcoa mainly for automotive chassis parts. "Riserless" means no mechanical feeding of melt into the mould. In addition, the level of melt in the feeding furnace is kept constant by replacing every shot from a holding furnace. Furthermore, the direction of solidification is controlled by active heating and/or cooling. Thicker sections can be fed directly in most cases, leading to lean gating systems. VRC / PRC castings have a dense, fine grained microstructure with excellent mechanical properties.

![Fig. 1: Elements of Alcoa's VRC/PRC process, schematically](image)
1.11.2 VRC / PRC – Process

Fig 2: VRC / PRC casting machine, schematically
Source: Alcoa

Fig. 3: VRC/PRC Gen III casting machine
Source: Alcoa
1.11.3 VRC / PRC – Processing of chassis parts

Fig. 4 is a flow chart of chassis parts production using VRC / PRC. The alloy most commonly used for this process is A356 / AlSi7Mg. First, raw material is analysed metallurgically. After melting, liquid aluminium is distributed by a channel system feeding furnaces equipped with impellers. From there the melt flows to dosage furnaces feeding the casting furnaces after every shot.

![Flow chart of chassis parts production](image)

After solidification the chassis parts are removed either manually (small parts) or robotically (large, heavy parts). Sawing and deburring is usually automatized. This is followed by X-Ray with automatic image analysis, heat treatment to achieve suitable mechanical properties, crack detection, eventually machining and shipping.
1.11.4 VRC / PRC – Mechanical Properties

See also:
- AAM – Manufacturing – 1 Casting methods > Vacuum die castings > Mechanical properties
- AAM – Manufacturing – 1 Casting methods > Green sand castings

Due to anti-gravity turbulence-free filling and directional solidification, the good microstructure leads to excellent mechanical properties. Some parts are used as cast, higher strength requirements are met after heat treatment.

<table>
<thead>
<tr>
<th></th>
<th>A356-F subframe as cast</th>
<th>A356-T64 knuckle heat treated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength (typical)</td>
<td>85 MPa</td>
<td>230 MPa</td>
</tr>
<tr>
<td>Ultimate Strength (typical)</td>
<td>150 MPa</td>
<td>300 MPa</td>
</tr>
<tr>
<td>Elongation (typical)</td>
<td>12 %</td>
<td>11 %</td>
</tr>
</tbody>
</table>

Mechanical properties can be adjusted by heat treatment to meet various requirements.

<table>
<thead>
<tr>
<th>Process Base</th>
<th>VRC / PRC</th>
<th>AVDC</th>
<th>AGSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Thickness</td>
<td>Low Pressure Die Casting</td>
<td>High Pressure Die Casting</td>
<td>Sand Casting</td>
</tr>
<tr>
<td></td>
<td>min. 4 mm</td>
<td>min. 1.6 mm</td>
<td>min. 3 mm</td>
</tr>
<tr>
<td>Max. Part Weight</td>
<td>50 Kg</td>
<td>20 kg</td>
<td>30 Kg</td>
</tr>
<tr>
<td>Typ. Heat Treatment</td>
<td>T 64</td>
<td>T 7</td>
<td>T6</td>
</tr>
<tr>
<td>Typ. Yield Strength [MPa]</td>
<td>230 MPa</td>
<td>140 MPa</td>
<td>210</td>
</tr>
<tr>
<td>Typ. Ultimate Strength [MPa]</td>
<td>300 MPa</td>
<td>200 MPa</td>
<td>270</td>
</tr>
<tr>
<td>Typ. Elongation [%]</td>
<td>11 %</td>
<td>15 %</td>
<td>7</td>
</tr>
</tbody>
</table>

Typ. Alloys:
- A356 / AlSi7Mg
- C448 / AlSi0Mg, C446 / AlMg3Mn
- A356 / AlSi7Mg

Fig. 5: Comparison of Alcoa’s automotive-oriented casting processes VRC / PRC, AVDC and AGSC
1.11.5 VRC / PRC – Examples of parts

See also:

AAM – Applications – 2 Chassis > Structure and components > Subframe / Rear axle

Knuckles from Generation II Machine:

A356 - T6
UTS - 276 MPa
YS - 207 MPa
EL - 8%
Source: Alcoa

Subframe produced with VRC / PRC: this part is a one piece casting approx. 1200 mm wide
Source: Alcoa
1.11.6 Ultra Large Caster (ULC)

The VRC process was developed by Alcoa during the 1950s. PRC was added during the 1980s. The Ultra Large Caster has been built during a further development effort targeting large castings.

The parts produced demonstrated the potential of the process: the tailgate weights 11 kg, replacing 11 stampings and reducing the weight by 25 % (at that time). Wall thickness was between 2.5 mm and 6 mm. The alloy in this case was A356-T5. Mechanical properties (TYE) were: 170 MPa, 130 MPa, 10 %.

Molds for this machine can be as big as 3400 mm x 1700 mm. This allows using a two-out die for parts like the tailgate below.

Cycle time was 2 minutes: this makes ULC economically attractive

Source: Alcoa
1.12 Lost foam castings

1.12.1 Introduction

Lost Foam Casting (LFC) or expandable pattern casting (EPC) involves the replacement of a low density foam pattern by liquid metal. LFC offers the possibility of a direct production of nearly any complex geometry including complicated undercuts and cavities without tapers and the need for considerable finishing work. Compared to the conventional sand casting methods it has economical and ecological advantages.

Initial applications of LFC have used patterns cut and milled from foam blocks to the same tolerances as conventional patterns. This process, called full mold process, was primarily used to produce large, one-only stamping dies in bonded sand. It is still used for rapid prototyping of intricate components or large castings. The actual LFC-process uses patterns of expandable polystyrene (EPS) for industrial applications. These patterns, directly foamed to shape, are immersed in a moulding box with binderless sand. The liquid metal, which is poured into the cups of the downsprues, vaporises the EPS pattern, which is precisely replaced by the metal. With the possibility of assembled patterns very complex shapes can be created and the castings can be reproduced with remarkable dimensional accuracy.

The steps of the production process, its application potential and the properties of LFC castings are described in the following.
1.12.2 Pattern making & cluster assembly

Pattern making. The initial material required for pattern making is expandable polystyrene (EPS). First step in the LFC-process is the pre-expansion of EPS beads.

After maturing the beads are blown into a mould forming the pattern sections. The mould is then steamed to expand the beads further and tightly fill the cavity of the mould. Hot steam and expansion of the beads causes them to weld together.

Cluster assembly. Complicated parts including undercuts and hidden cavities cannot be moulded in one working step, but are assembled from pattern segments into a final pattern. Joining techniques used are gluing, heated platen welding and plugging. In order to increase the efficiency of the total process several patterns are combined into a cluster and supplied with a common gate system, also made of EPS.
Pattern molding unit
Source: LWF/ZVG Paderborn

Pattern assembly
Source: BMW AG Landshut

Cluster with two cylinder heads
Source: BMW AG Landshut
1.12.3 Coating & embedding

**Coating:** The clusters are coated with a refractory coating layer by immersion in a water soluble ceramic slurry. The coating layer has the function of guiding the gasification process of the pattern and to form a barrier between the moulding material and the gas-filled bubble which exists between the still solid EPS-pattern and the intruding aluminium melt. After the coating has dried, a thin, hard and permeable coating remains. The coatings are typically applied to a foam cluster by dipping, spraying or pouring.

**Embedding in sand:** After the coating has dried, the cluster is placed in a flask and backed up with unbonded quartz sand without chemical additives. The sand is compacted through vibration with various frequencies, which causes the sand to fill all hidden cavities of the patterns.

![Production steps](image1)

**Source:** LWF/ZVG Paderborn

![Coating of a cluster with two cylinderheads](image2)

**Source:** BMW AG Landshut
1.12.4 Pouring & finishing

Pouring: During the filling process the molten metal flows via the gate system into the EPS-patterns, which is gasified, filling up the cavity and replacing exactly the pattern geometry. During this stage it is important to avoid turbulences, support the casting cavity wall and to realise a progressive elimination of the foam pattern. The gas originating from EPS decomposition permeates the coating layer and escapes into the sand, possibly supported by an external vacuum (see schematic fig. above). Form filling velocity and type of metal flow, i.e. laminar or turbulent, determine the part's quality by influencing the amount of oxide inclusions and porosity. Specifically, the following sets of parameters have to be tuned to each other:

- permeability of coating,
- optional external vacuum,
- metal temperature,
- EPS-pattern density and type of adhesive,
- geometry of the gating / riser system and of the patterns.

Dumping, quenching and trimming:
After solidification of the casting, the sand can be removed from the flask and be prepared for the following moulding. Clusters are quenched and knocked-off from the gate system. The castings are purged and controlled w.r.t. defects. In many applications the castings don’t require any further mechanical finishing.
Production steps
Source: LWF/ZVG Paderborn

Experimental foundry for lost foam casting at the University of Paderborn

Pouring by hand for experimental or short runs
Source: LWF/ZVG Paderborn
1.12.5 Advantages and disadvantages

Advantages:
- freedom of design, possibility to build-up complicated geometries by assemblies of several EPS parts,
- no draft angles necessary,
- no burrs, less cleaning of castings,
- reduction of amount of machining,
- binder-less recirculated sand,
- reduced environmental burden,
- potential for Rapid Prototyping,
- economy,
- dimensional accuracy and less finishing work,
- no sand reclaiming system,
- long life of moulding tools for EPS patterns (up to 1 mio.),
- high productivity,
- high flexibility,
- good surface quality.

Disadvantages:
- possible deformation of pattern during sand fill and compaction,
- possible entrapment of plastic residues caused by non-optimised gating systems,
- large number of process parameters need to be controlled for optimum form filling.
Source: Albert Handmann
### 1.13 Comparing casting techniques

<table>
<thead>
<tr>
<th>Criteria</th>
<th>green sand</th>
<th>Chemical bonded</th>
<th>Lost foam</th>
<th>Core package</th>
<th>Gravity die casting</th>
<th>Low pressure die casting</th>
<th>High pressure die casting</th>
<th>Vacuum die casting</th>
<th>Squares casting</th>
<th>Third casting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum standard weight of parts (kg)</td>
<td>60</td>
<td>60</td>
<td>20</td>
<td>50</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>35</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Reason for dimensions limitation</td>
<td>Tolerances on large dimensions</td>
<td>Dimensions and weight of moulds</td>
<td>Closing strength of machines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Possibility of cast cores</td>
<td>E</td>
<td>E</td>
<td>A</td>
<td>A</td>
<td>C</td>
<td>C</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Minimum standard thickness (mm)</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Local minimum thickness</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>1.5</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Dimensional accuracy</td>
<td>D</td>
<td>D</td>
<td>C</td>
<td>B</td>
<td>C</td>
<td>C</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>TF class (%)</td>
<td>12.1</td>
<td>6.3</td>
<td>6.3</td>
<td>6.3</td>
<td>6.3</td>
<td>6.3</td>
<td>5.8</td>
<td>8</td>
<td>8.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Surface roughness (Ra in µm)</td>
<td>12.5</td>
<td>8.3</td>
<td>6.3</td>
<td>5.6</td>
<td>6.3</td>
<td>6.3</td>
<td>8.0</td>
<td>1.8</td>
<td>1.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Thermal treatment possible or welding</td>
<td>(C)</td>
<td>(C)</td>
<td>+</td>
<td>+</td>
<td>(C)</td>
<td>+</td>
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<tr>
<td>Rating of gas content/pores (low, medium, high)</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>B/C</td>
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<td>A</td>
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<td>Sections</td>
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<td>C</td>
<td>C</td>
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<td>B</td>
<td>A</td>
<td>T</td>
<td>B</td>
<td>A</td>
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<tr>
<td>Castability</td>
<td>Good</td>
<td>Acceptable</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
<td>Acceptable</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
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</tr>
</tbody>
</table>

1. Forging on cost.
2. Some foundries have developed special core making methods and adequate casting process parameters, like Honda with the "New Die Casting" (NDC).
3. According to IGGI standard.
4. Depending on the possibility of using a smooth coating.
5. Notwithstanding distortion problems.
6. Pressure die cast parts are generally low elongations, due to scattered porosity and inhomogeneity of the material and design (see 7).
7. Alloys used for pressure die casting are mostly secondary alloys, as iron from core has a 0.5% in other alloys and is mandatory towards problems of aluminium sticking to the mould.
8. Always subject to hot-tearing.
9. Lost foam allows casting of several parts in a single operator, depending on the size of each part and the volume of the sand tanks.
10. For a standard part.
1.13.1 Comparing casting techniques for engine blocks and cylinder heads

![Diagram comparing casting techniques for engine blocks and cylinder heads.](source: VAW AP)

**Design possibilities**

<table>
<thead>
<tr>
<th></th>
<th>High pressure</th>
<th>Low-pressure</th>
<th>Die</th>
<th>Core package</th>
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</thead>
<tbody>
<tr>
<td>Integration of oil flange</td>
<td>no</td>
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<td>Thermostat housing</td>
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<td>PCV housing</td>
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<td>Splashwall</td>
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<td>Curved oil channels</td>
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<td>Complex structures</td>
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<td>Weight reduction by core inserts</td>
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<td>Bearing surface treatment</td>
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</table>

*Source: VAW AP*