Cylinder Block and Head Materials and Manufacturing

7

Before addressing cylinder block and head layout design it is important to understand the restrictions imposed by material and casting process selection. This chapter begins with a brief look at the aluminum and gray iron alloys typically used for cylinder blocks and heads. Magnesium alloys, and composite blocks with magnesium portions are receiving increased attention for weight reduction, and will also be briefly covered. Many of the design constraints are imposed by the capabilities of the chosen casting process, so the commonly used casting processes will next be introduced. The chapter concludes with an overview of the machining lines used for block and head production.

7.1 Cylinder Block and Head Materials

For many years the vast majority of automobile, truck, and agricultural and construction engines used cylinder heads and blocks that were sand cast from gray iron. While sand cast gray iron components remain important, automobile applications are seeing increased use of aluminum, and a variety of casting processes. Most new automobile engines use aluminum cylinder heads, while at this writing new engine block designs are closely split between aluminum and cast iron. This section begins with a look at gray iron and related alloys. Aluminum alloys are then discussed.

7.1.1 Gray Cast Iron

A variety of irons and steels including gray and ductile iron are alloyed from iron, carbon and silicon. Further alloying elements may be added to provide specific properties desired for a particular application. Some of these elements will be discussed later in this section.

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DOI 10.1007/978-3-7091-1859-7_7

Both gray and ductile iron alloys have relatively high carbon and silicon content as compared to steel—between 2 and 4% carbon is typical, whereas 1% is considered "high carbon" in steel. Even with its much higher carbon content gray iron is relatively soft and easily machined. Its properties also differ considerably from those of ductile irons having very similar carbon content. These facts suggest that there is much more that distinguishes these materials than carbon and silicon content alone. The differences can be far better explained by examining the micro-structure of each.

In both gray and ductile iron the carbon precipitates out of the molten metal as graphite (as opposed to carbide in the case of steel). The gray iron alloys of interest for cylinder blocks and heads consist of mixtures of ferritic and pearlitic iron phases from which the carbon has precipitated out as graphite flakes as shown in the left photograph of Fig. 7.1. The silicon in the alloy creates precipitation sites controlling the size and distribution of the graphite flakes—increased silicon results in a finer distribution of smaller graphite flakes, generally resulting in increased strength. The resulting gray iron alloy is a low cost material that is relatively easy to cast and machine. The graphite flakes are resistant to shear between the iron crystals, and result in very high compressive strength. However these same graphite flakes provide crack initiation sites, reducing the tensile strength of the material. This will be an important consideration in designing engine components from gray iron.

By using a special ladle to add controlled amounts of magnesium to the melt as a casting is being poured the carbon can be made to precipitate out of the iron in the form of graphite spheres. This is shown in the photo at right in Fig. 7.1. The resulting alloy is ductile iron. The spherical graphite results in a considerably higher tensile strength than that of gray iron. However the material is more difficult to cast and machine and is considerably more expensive than gray iron. In engines ductile iron is often used for piston rings, exhaust manifolds, and main bearing caps. In every case the material is chosen for its increased tensile strength; for example, the firing forces result in high tensile loads in

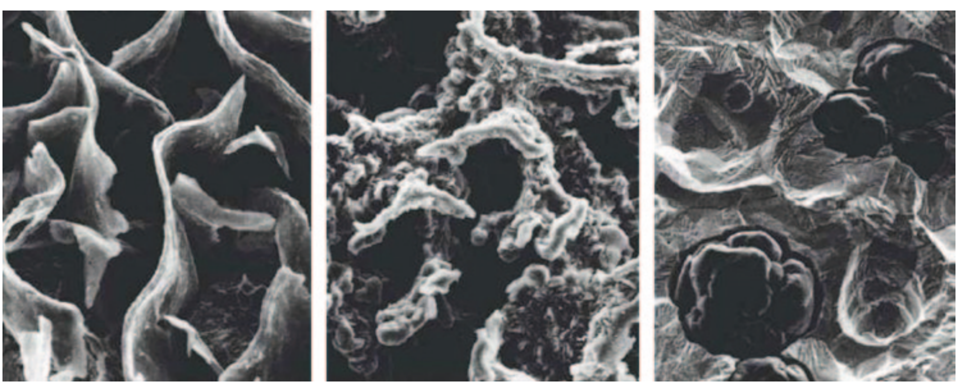

Fig. 7.1 Representations of *grey* iron (*left*), ductile iron (*right*), and compacted graphite (*center*) micro-structure

the main bearing caps, so while the block is cast from gray iron, the caps may be cast from ductile iron.

Returning briefly to gray iron casting and alloying, as the melt temperature drops after the casting is poured the carbon begins precipitating out when the ***graphite eutectic temperature*** is reached. The solidification process must then be completed before the temperature drops below a lower temperature termed the ***carbide eutectic temperature.*** If any carbon remains in the liquid phase when this lower temperature is reached it will solidify as carbide. An important aspect of gray iron castability is completing the solidification process within this temperature window. In complex castings thin sections may cool too quickly, rapidly dropping below the carbide eutectic temperature and thus forming carbide. Thick sections may solidify so slowly that carbides appear side by side with the graphite. Several alloying elements—copper, nickel, and cobalt—can be added to increase this window and improve castability. Copper is often especially favored, and its content must be carefully monitored as high copper content hurts fatigue strength.

Other alloying elements of interest include chromium and molybdenum. Chromium is sometimes added to gray iron to increase its strength. However it makes the material more difficult to cast as it reduces the temperature window discussed in the preceding paragraph, and it makes machining more difficult. Molybdenum is now quite often added to gray iron cylinder heads to improve high temperature fatigue life; it too reduces machinability.

Another iron alloy rapidly growing in usage for cylinder blocks is compacted graphite. While new to engine blocks compacted graphite was patented at the same time, by the same metallurgists as ductile iron. The year was 1948, and both materials were developed by introducing controlled quantities of magnesium to the melt. The middle photograph in Fig. 7.1 shows the intermediate graphite structure of compacted graphite. Where gray iron has a flake structure, and ductile iron a nodular structure, compacted graphite is described as a worm, or noodle structure. It has been kept from production applications until recently primarily due to casting process control. It should not be surprising that the structure is achieved through controlled magnesium introduction, but the problem lies in its close control. Too much and the nodular structure appears; too little and it reverts to the flake structure. Compacted graphite iron is specified as having no graphite flakes, and under 20 % nodularity.

The primary attractions for cylinder blocks are a higher tensile strength and greater resistance to wear of the cylinder wall surfaces. It should be noted that while compacted graphite has nearly twice the strength of gray iron, ANY presence of graphite flakes causes the tensile strength to plummet. This should not be surprising as one thinks of the role of graphite flakes in tensile failure as discussed relative to gray iron.

The next challenge is that of machining. The low tensile strength of gray iron makes it easy to machine. However, there is another important factor. All iron ores contain sulfur, and in the melt the sulfur is free and easily combines with oxygen and manganese. The iron ore contains manganese as well, and the resulting manganese sulfide coats the cutting tool. In compacted graphite two factors remove this mechanism. First, process control requires beginning with significantly lower sulfur ores. Second, the sulfur preferentially reacts with the magnesium introduced to the melt, thus taking away the role of manganese sulfide. The results are increased machining difficulties on several fronts. The approach that has initially been taken is to go to significantly higher feed rates to overcome machining resistance, and lower speeds to improve tool life. This combination allows volumes to be maintained, but requires very different fixture design, precluding running gray iron and compacted graphite parts on the same lines. The most recent approach has been to introduce tool heads with multiple cutting tools. By simultaneously cutting at several locations the feed rate can be reduced and the same overall metal removal rate can be achieved.

The increased strength, and the resulting ability to make much thinner, lower weight castings more than offsets the increased material, casting, and machining cost in many applications. Typical minimum wall section for cast iron is 4.5 mm thick, but as casting technology improves the material properties will allow 3 mm wall thicknesses, which open further possibilities for weight reduction. This weight reduction can be enabled because the minimum wall thickness is often limited by the casting process, while that actually required by the design, especially when using compacted graphite, might be significantly less.

7.1.2 Aluminum Alloys

The use of aluminum alloys has historically been driven by weight reduction, and it has been most often seen in high performance engines. Switching from cast iron to aluminum cylinder heads lowers the center of gravity of the engine in a vehicle, improving handling. More recently the combination of weight, thermal conductivity, and cost reduction has resulted in its use in many more automobile engines. An aluminum engine block will typically weigh between 40 and 55 % less than a comparable gray cast iron block. While the raw material cost of aluminum is higher than that of gray iron, and the energy required to produce aluminum from bauxite is high, this is offset by reduced final processing costs and a high degree of recycling. The lower casting temperature reduces the energy required to melt the material, and makes permanent mold and die casting processes possible, further reducing the cost of high volume parts. Finally the machining costs are reduced as tool life is increased relative to that for gray iron. The different thermal expansion rate of aluminum to cast iron for cylinder blocks is both a benefit to piston-to-cylinder fit, and a hindrance to maintaining crankshaft main bearing clearance. Aluminum alloys have three to four times greater thermal conductivity compared to gray iron, making it especially attractive for cylinder heads. The primary disadvantages of aluminum include its lower stiffness, high temperature creep relaxation, and poor wear characteristics relative to iron. Special design considerations must take these challenges into account.

Most aluminum alloys of interest for use in engines include copper (up to 5 %) and silicon (as much as 18 %). Slow cooling of aluminum and copper alloys results in the copper forming a separate "theta" phase along the "alpha" phase boundaries of the alloy, as

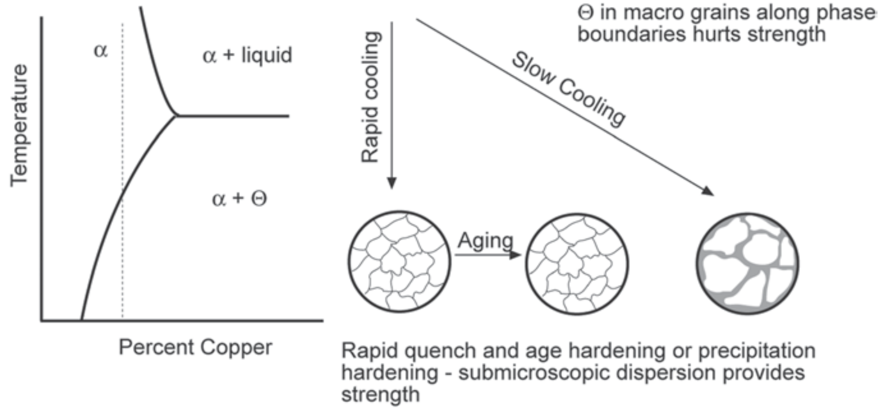

Fig. 7.2 Age hardening of aluminum-copper alloys

depicted in Fig. 7.2. This separate phase hurts casting strength, and can be minimized by rapid cooling or "quenching"– at least in the regions where strength is most critical. Under rapid cooling the copper forms a sub-microscopic dispersion. The alloy is subject to a further heat treatment (age hardening) in which the copper comes out of solution, but remains finely dispersed, thus minimizing the material's loss of strength. The silicon forms dendrites as it solidifies, and rapid cooling reduces the size and spacing of the dendrite arms; this too improves the alloy strength. The need for rapid cooling in critical regions, in order to achieve optimal strength, must be kept in mind as casting processes are discussed in the next section.

Because of the inherently poor wear characteristics of aluminum its use as a cylinder block material requires special cylinder wall considerations. In most cases this is addressed by casting iron alloy cylinder liners into the block. Aluminum 356 is the most typical alloy for such cylinder blocks. This alloy has no copper and only small amounts of silicon and magnesium, and is very easy to cast. Another approach increasingly seen for cylinder blocks is to use a high silicon alloy such as Aluminum 390. This alloy contains 17 % silicon and 4.5 % copper, in addition to small amounts of magnesium and manganese. The hyper-eutectic silicon content results in silicon particles that significantly increase hardness and provide an acceptable cylinder wall running surface. For scuff resistance the aluminum pistons are then coated with a thin layer of either iron or chromium. Another approach involves casting the cylinder walls from high silicon alloy aluminum and then surrounding them with a lower silicon alloy such as 356. This approach requires a casting process (typically die casting) that rapidly cools the molten block alloy before it can re-melt the cylinder walls.

An important requirement of the cylinder head casting is high temperature fatigue strength, and Aluminum 319 is commonly used. This alloy contains a small amount of silicon and about 4.5 % copper. The casting process often includes the use of a water cooled "chill plate" to rapidly cool the casting at the firedeck surface, to disperse the alloying elements as shown in Fig. 7.2, reduce porosity, and increase density and material strength. Minimum wall thickness for cylinder head and engine block castings based on casting process capability is typically 2.5 mm; greater thicknesses are structurally required in many sections.

7.1.3 Magnesium Alloys

At this point in time production uses of magnesium have been limited to smaller engine components such as intake manifolds and covers, or have been limited to use in racing engine blocks where the higher cost of material and lower resistance to corrosion are less of a concern. It is beginning to generate interest as a cylinder block and head material for production engines. Its primary attraction is in providing the greatest potential for weight reduction while providing adequate strength. Estimates have suggested the resulting engine to be on the order of 25% lighter than a comparable all aluminum engine, assuming the entire block and head could be made from magnesium. Design concerns include structural stiffness, cylinder wall characteristics, temperature limits, hot creep, corrosion resistance, casting control, and machining. Galvanic corrosion may occur when in contact with dissimilar materials, especially steel. One example engine has switched to aluminum fasteners to avoid this. Limited fatigue data, and an especially limited understanding of its high temperature capabilities add to the design challenge. Initial production use for cylinder blocks will be in conjunction with other materials to address the concerns just listed.

Material properties can vary widely based on alloy content and heat treat, some representative values are shown below in Table 7.1 for comparison purposes.

Table 7.1 Material property comparison

Material	Density (g/cm^3)	Ultimate tensile strength (MPa)	Modulus of elasticity (GPa)	CTE, linear (µm/m-°C)	Thermal conductivity (W/m-K)	Relative material cost	Relative noise absorption
Gray cast iron	6.8–7.3	120–350	70–140	12–15	45–50	1.0	Best
Ductile cast iron	6.6–7.4	345–650	130–170	10–18	10–30	1.6	Good
Compacted Graphite Iron (CGI)	7.0-7.3	250–650	120–160	11–12	30–40	–	Good
Aluminum alloys	2.6–2.9	160–280	64–75	24–27	90–210	2.5–5.5	Poor
Magnesium alloys	1.8	90–230	40–50	26–30	160	3.6-6.0	Poor

7.2 Cylinder Block and Head Casting Processes

If it were possible to design the engine based solely on casting considerations each part would be designed such that reusable molds would define every feature. The exterior features of the part would be designed such that the molds could be pulled straight from the part in each direction. Even the number of directions from which the molds were to be pulled would be minimized. Clearly such requirements would compromise the exterior dimensions of parts such as cylinder blocks and heads, and they would further compromise or eliminate interior features. Before rejecting such requirements as totally unrealistic it should be noted that in small, high volume industrial engines such requirements are actually quite common, and do in fact constrain the design of the engine. However, in multi-cylinder automotive engines the compromises become unacceptable, and casting processes allowing the required design complexity must be found. The typical processes used for automotive cylinder blocks and heads are described in the paragraphs that follow.

7.2.1 Sand Casting

For many years this has been far and away the most commonly used production casting process for both aluminum and gray iron engine blocks and heads. The technology is very well developed, and the process allows intricate shapes, undercut geometry, and hollow cavities to be produced. The process involves creating a mold (negative of the part to be cast) made from a mixture of sand, bentonite clay, and water. The mold is packed around a steel pattern, and the pattern is then removed, creating the hollow cavity. Engine parts are typically created using a cope and drag mold, the features of which are shown in Fig. 7.3, where the cope and drag form the upper and lower portions respectively of the part to be cast. Interior cavities are created using cores molded from sand and an adhesive binder, or

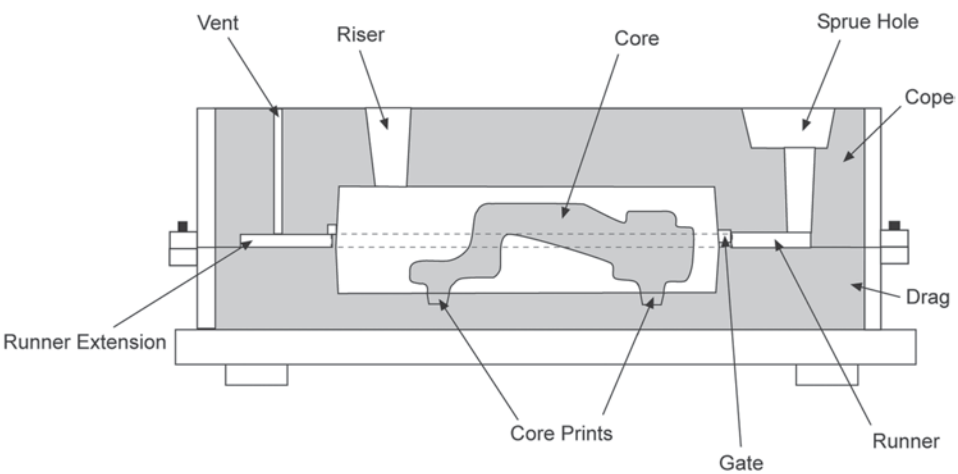

Fig. 7.3 Schematic of cope and drag mold for sand casting

are made from salt. The cores are held in place using locating tabs known as ***core prints*** as shown in Fig. 7.3. The core sand will later be removed from the casting at these print locations. The molten metal is poured into the cope and drag mold through the sprue hole. The metal flows through a series of runners around the perimeter of the mold, and is fed into the mold cavity through gates that have been placed and sized in such a way to optimize the fill rate and resulting properties of the casting. Runner extensions allow the initial portion of the melt to flow past the casting before the molten material flows through the gates into the casting. This is done because the melt from the top of the pouring ladle often contains impurities that would hurt the casting properties. Risers at various locations provide columns of material designed to compensate for shrinkage and resulting porosity as the casting cools. The sand itself must be porous to gas, allowing air from within the mold cavity, and gases from the core adhesives to escape from the mold.

Once the casting solidifies the sand is broken away from around the casting, and cleaned from the cores. The complex casting geometry results in various portions of the casting cooling and solidifying at different rates. This in turn creates residual stresses that are eliminated by annealing the casting. Because the sand surrounding the casting serves as an insulator the annealing process is often accomplished by allowing the casting to remain surrounded by the sand for several hours after solidification. This is quite commonly done with cylinder block castings to reduce the casting process costs.

Because a new sand mold must be created for each part to be cast the sand casting process is relatively expensive, especially for high volume production. The resulting surface is rough as compared to that achieved with the other processes to be described, thus increasing machining requirements and further increasing costs. Further production challenges include the gas and shrinkage porosity identified earlier. Core shift or core float—the movement of cores within the mold—sometimes causes problems as well. Finally, sand cleanout, especially from relatively small passages such as cylinder head cooling jackets may create production problems.

7.2.2 Permanent Mold Casting

As production volumes increase the use of permanent molds instead of sand molds becomes attractive. If the part is to be cast from aluminum, steel molds can be designed to pull apart from the casting. These molds can be used to create any surface from which the solid mold can be directly pulled, which restricts the use of undercut geometry. Interior cavities can be produced by using disposable cores in conjunction with permanent molds. This combination is termed semi-permanent mold casting. The resulting surface finish is very good, and chill plates can be incorporated in the molds to improve strength in critical regions.

7.2.3 High Pressure Die Casting

Another form of permanent mold casting is die casting. Where the molten metal in permanent mold casting is gravity-fed, the metal is rapidly injected into the mold under high pressure in die casting. Wall thickness as little as 2.5 mm can be achieved. High Pressure Die Casting is attractive for further cost reduction in high volume production due to short cycle times, and is used for many aluminum engine parts. However, because of the rapid feed rate disposable cores are not typically used. During the high pressure die casting process a thin layer of metal quickly coats the mold surface and solidifies creating a dense skin. As the material beneath the surface solidifies, the resulting shrinkage creates porosity, and a distinct surface and sub-surface layer of markedly different material properties results. It is desirable to core oil and coolant passages and to avoid drilling into thick sections where porosity is present.

7.2.4 Lost Foam Casting

A relatively new process of rapidly increasing interest for cylinder blocks and heads is lost foam casting. This process can be used for both aluminum and gray iron casting although at this writing its production use for blocks and heads has been limited to aluminum.

Lost foam casting begins with an expandable polystyrene (EPS) model of the exact part to be cast. The EPS part includes all internal and external features of the final part. Its complexity can be increased by creating the EPS mold in several parts and then gluing them together. The EPS mold is then dipped in a refractory ceramic, covering the entire mold with a thin layer. The mold is then packed in loose sand. Finally, the molten metal is poured on the EPS mold causing it to vaporize, and replacing the mold with the cast metal part.

The resulting part has excellent dimensional stability, thus minimizing further machining. The part complexity that can be achieved often allows parts that would otherwise be made separately to be included as a single casting. This too reduces machining, as well as reducing assembly cost and eliminating gasketed joints. More intricate oil and coolant passages can be incorporated into the mold. A well-designed lost foam casting may result in reduced costs as compared to sand casting or permanent mold casting.

One disadvantage of lost foam casting is the inability to use cooling plates to improve the local properties of an aluminum casting. Another potential disadvantage results from the glue lines on the EPS mold and potential for core shift during gluing. These must be closely controlled to avoid detriments in the final part such as stress concentrations.

7.2.5 The Cosworth Casting Process

Originally developed for Formula One racing engines, the Cosworth process holds the attractions of very close dimensional control and the ability to cast very thin wall sections. The process is limited to non-ferrous alloys. The melt is supplied under controlled pressures to a zircon sand mold. The zircon mold is mixed with a binder and cured, resulting in the ability to control dimensions closely. The pressurized melt is supplied through gates to the base of the mold, and the controlled pressure and gate design results in a casting virtually free of porosity and inclusions. The process is now seeing some use for high volume production cylinder blocks.

Not common in the automotive industry, but occasionally used in aircraft and locomotives, are forged or welded engine blocks. For radial piston aircraft engines, the block halves are forged from steel for strength. For very large engines, blocks are sometimes fabricated by welding thick sheetmetal sections together. While the labor is time consuming and expensive, this typically lowers the weight of the engine block on the order of 10 % versus a cast block for the same application.

In concluding this section it must again be emphasized that many of the design features seen in cylinder blocks and heads are driven directly by the chosen casting process. Wall thicknesses and radii, and the placement of cooling jacket openings (core prints during casting, and pressed in "freeze plugs" to seal coolant passages on the final part) are examples. The shapes of passages and features from which permanent molds must be pulled are also examples. A comparison of casting methods is shown in Table 7.2.

Table 7.2 Comparison of casting methods

Process	Tooling	Labor	Piece cost	Typical economical quantities	Dimensional accuracy
Sand casting	Low	Med	Med	Small-Large	Low
Permanent mold casting	Med	Low	Med	Med-Large	Med
High pressure die casting	High	Low	Low	Very Large (>10,000)	High
Lost-foam casting	Low	Med-High	Med	Small-Med	Med
Cosworth casting process	Med	Med	High	Small-Med	High

7.3 Cylinder Block and Head Casting Design Considerations

In general, it is important to minimize the weight of cylinder block and cylinder head castings, as these components are typically the heaviest in the engine assembly. It is good practice to avoid abrupt transitions from thick to thin sections and sharp corners in a casting, as these lead to difficulty flowing molten metal into the mold, and later lead to stress concentrations when the metal has cooled. For the cylinder block, it is important to avoid large flat panel sections, as these radiate noise. It is best to break these features up by curving the surface or adding ribs. ***Casting draft*** angle is a slight taper given to the mold surfaces perpendicular to the parting line to allow the easy removal of the casting, and is a key design consideration. The goal is to minimize machining on surfaces with a lot of casting draft, as this leads to excessive stock removal and could expose casting porosity.

During the design of the casting, it is common practice to employ casting simulation software. Casting simulation can predict flow patterns and velocities of metal filling the mold cavity, and can predict which areas of the casting will solidify first. This will often influence the final geometry of the part at an early design stage, and reduce the need for casting trials at later stages of development. Bearing bulkheads and cylinders in the block, the combustion chamber wall in the cylinder head, and the gates and runners in the die, are the main areas of focus (Fig. 7.5).

Figure 7.4 provides a simplified look at cylinder head casting for a water-cooled, dual overhead cam design seen in many automotive engines. The complexity of the needed port and cooling jacket geometry necessitates the use of non-permanent cores. The vast majority of engines in production today use sand cast cylinder heads. Semi-permanent molds—permanent dies for the outer dimensions, in combination with sand cores for the ports and cooling jackets—are used in a few applications. Lost foam is seen in a few

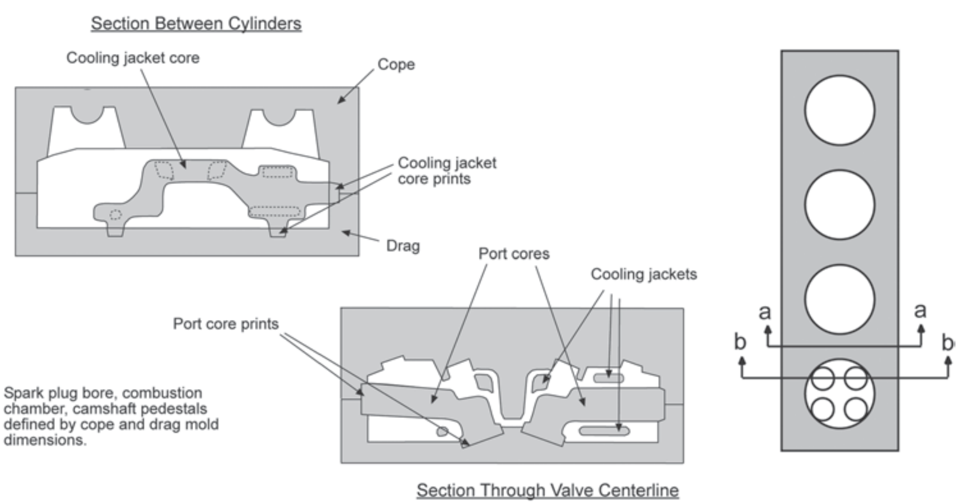

Fig. 7.4 Schematic depicting cylinder head casting considerations

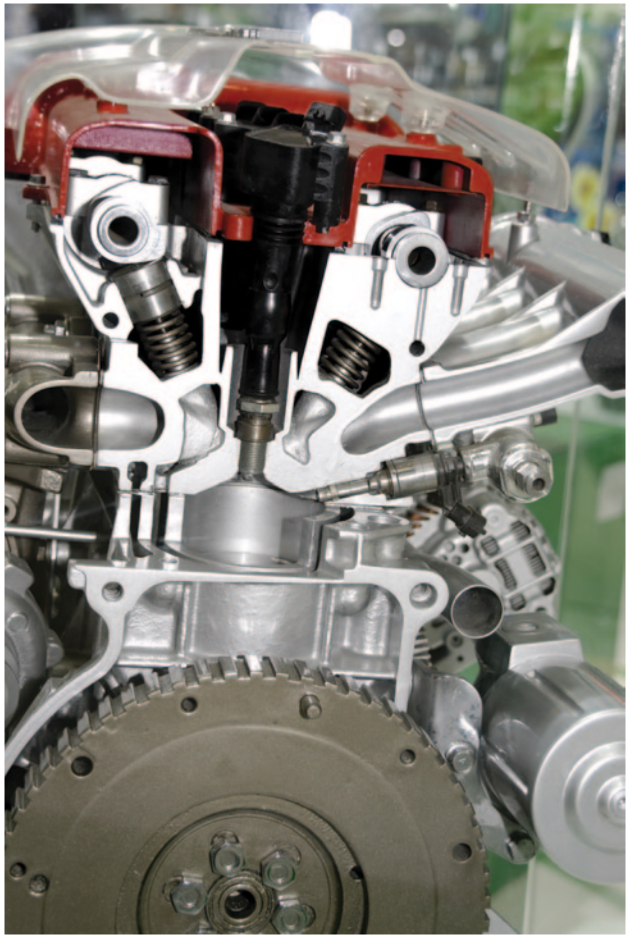

Fig. 7.5 Cylinder head casting cut-away

production applications, and might see increasing use. The figure shows a cope and drag mold, and depicts two sectional views—one through a port centerline and one between two cylinders. The as-cast dimensions of the outer perimeter, including the combustion chamber, spark plug bore, oil deck, and camshaft pedestals are determined by the cope and drag mold. The ports and cooling jackets are created with sand or salt cores. In the case of the ports the core print locations are quite straight-forward as the ports must be open to both the combustion chamber and the manifold flanges. The cooling jackets will be open to the cylinder block so in many engines core prints will be placed along the firedeck surface as shown in the figure. However, these will not be sufficient, either to hold the cores in position or for sand clean-out after casting. One additional core print will be located naturally by the coolant exit from the cylinder head to the thermostat housing. Further core prints are typically required at various locations along the sides of the head, an example of which is shown on the right side of the section between cylinders in Fig. 7.4. An example cylinder head casting cut-away The reader is encouraged to return to Figs. 1.6, 1.7 and 1.8

Fig. 7.6 A closed deck cylinder block

for examples of production cylinder heads; look particularly at the placement of the cooling jackets and ports. Cylinder head design will be covered in greater detail in Chap. 9.

A closed deck cylinder block is shown in Fig. 7.6. The geometry of the cylinder block as shown suggests that either sand or semi-permanent mold casting will be required. If aluminum were selected as the block material, the crankcase, cylinders, and outside surfaces could readily be designed such that permanent molds could be pulled directly away from the casting. The cooling jackets of a closed deck engine require non-permanent mold cores as further depicted in Fig. 7.7, increasing the cost of the casting. The primary benefit of the closed deck engine design is to provide a structure to better support the top of the cylinder

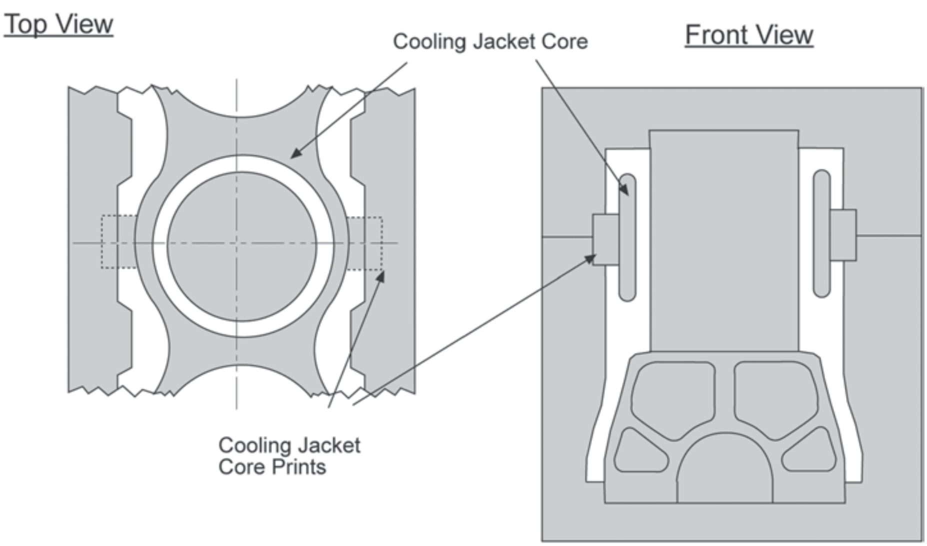

Fig. 7.7 Closed deck casting schematic

Fig. 7.8 Open deck cylinder block

and head gasket. Due to combustion and inertial loads, the piston applies a radial thrust load on the cylinder, making the top of the cylinder deflect. This movement will fret the cylinder head gasket, which may lead to leaks if not limited by axial clamping load on the cylinder or radial support from the closed deck design. Additionally, a closed deck design will affect the cylindricity of the bore, due to radial growth from thermal loads. Thorough design is required to meet targets for cylindricity of the bore.

An open deck design is shown Fig. 7.8, and a casting schematic is shown in Fig. 7.9. Similar to the closed deck design, the outer surfaces are easily addressed with a permanent mold. The main difference is that the cylinder cooling passages are also created using permanent molds. No sand cores are required, which reduces tooling and piece costs. Production examples of each are shown in Figs. 1.6, 1.7 and 1.8. In addition to reducing costs relative to the closed deck design, the open deck allows improved cooling at the top part of the cylinder and the interface with the cylinder head. However, careful attention must be

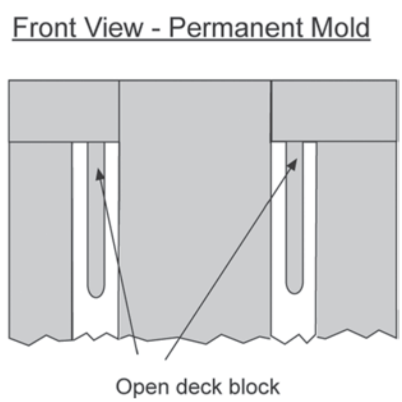

Fig. 7.9 Open deck casting core schematic

paid to the design of the head gasket to handle cylinder deflection due to piston thrust, and a multi layer steel (MLS) head gasket is typically used. Depending on the design of the cylinder block, it may decouple the deformation of the cylinder due to cylinder head bolt loads and thermal loads. In summary, an open deck design is less expensive and provides better cooling, but at the sacrifice of block stiffness. Cylinder block design will be covered further in Chap. 8.

7.4 Cylinder Block and Head Machining Processes

While advances continue to be made in flexible and computer controlled machining, engine parts are produced on fixed tooling for all but the lowest production volumes. It is important to involve manufacturing support as early as possible in the engine design process to balance the design requirement to the manufacturing capability, to enable the least expensive tooling and fixturing. Once the design is released for production, the majority of the cost is designed in and the cost of an operation rises exponentially with tighter tolerances. The type of fixturing and tooling will significantly influence the design, in order to achieve minimum cost. Frequently, a new engine design will be constrained to use existing tooling. While this drives compromise into the engine design, it reduces the overall cost to manufacture a new engine, which is important for the competitiveness of the business. The manufacturing lines for both cylinder blocks and heads are made up of a series of machines linked together in transfer lines. Each machine is constructed to repeatedly perform fixed operations specific to the particular part being produced. An example cylinder block transfer line is depicted in Fig. 7.10. The raw castings enter the "rough" end of the machining line, and the first machining operations establish the dimensional framework from which all further operations will be done. Locating "pads", or datums, on the casting are used to establish the reference position in 'x,' 'y,' and 'z' coordinates, and locating holes are drilled. It is important for these datums to be stiff, locate the part in all six degrees of freedom, and be as wide apart as possible. Each of the further machines in the transfer line will fixture the part by using pins fitted into these holes.

The transfer line begins with rough machining. A variety of operations are done at each machine, based on two criteria. The first is that of cycle time—the time required to complete all of the operations at each machine should be similar in order to avoid stacking parts up between machines or slowing the entire line down because of longer machining times required at a particular machine station. The second criterion is to minimize the number of times the part must be moved and again fixtured. In order to maintain the closest dimensional control it is desirable to maintain the part in a given fixture for as many operations as possible, as each time the part is re-fixtured it adds to the tolerance accumulation. While a given surface is exposed, conducting all of the operations on that surface is desirable. Where possible, it is desirable to dimension a part in whole degrees, as machining at fractional angles adds cost to the type of machining center required.

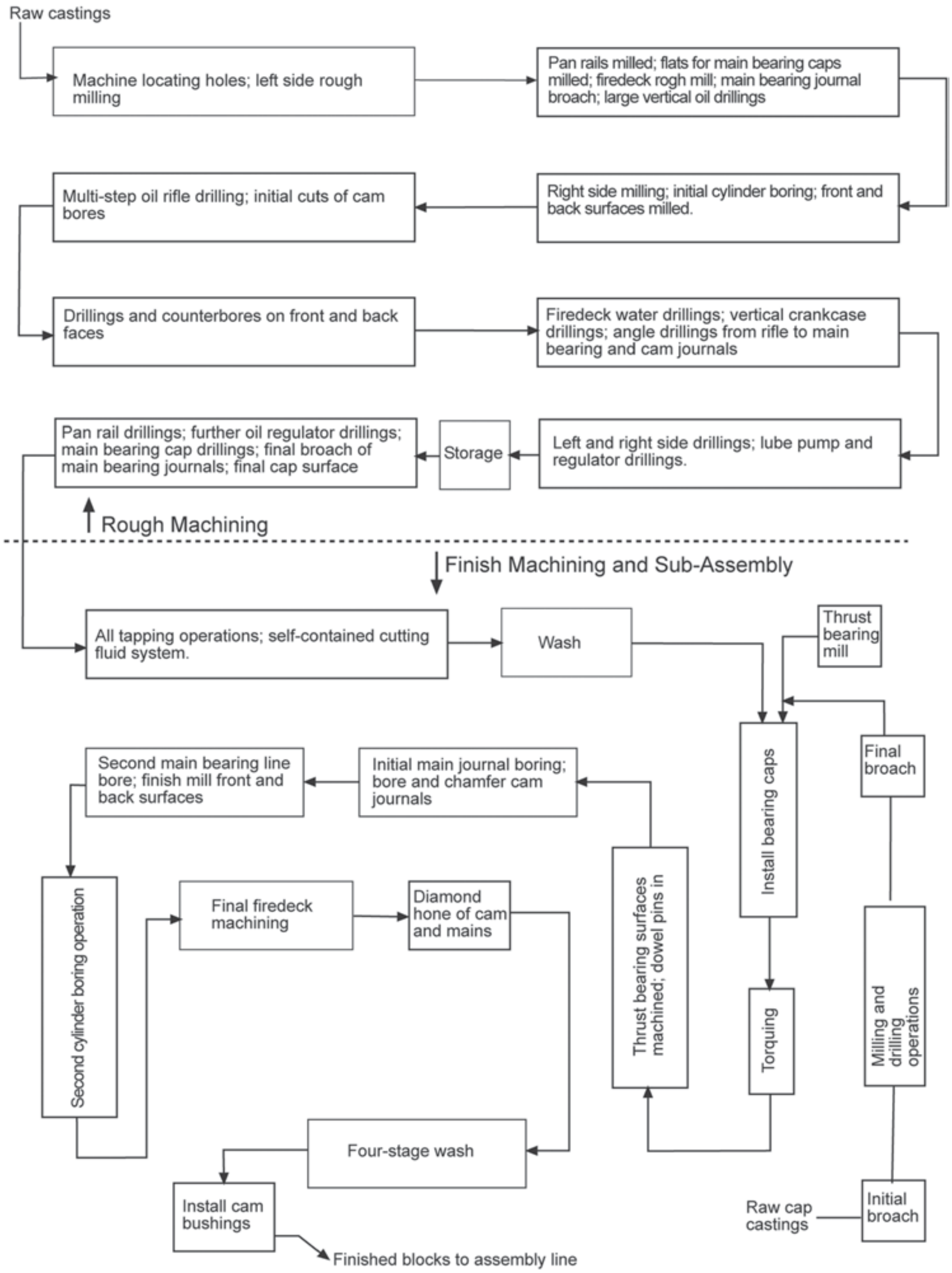

Fig. 7.10 Layout of a typical high-volume cylinder block machining line

Most machining lines begin with a series of rough operations, followed by an initial wash and then finish operations. Several of the finish operations are especially critical to the later performance of the engine. The effect of critical cylinder head dimensions include the concentricity of valve seats-to-guides on valve sealing; surface finish of firedeck machining on head gasket sealing; and the machined firedeck distance to the as-cast combustion chamber on the compression ratio from engine-to-engine. The effect of critical block dimensions include main bearing journal-to-journal alignment on bearing life; main bearing journals to cylinder bore alignment effect on cylinder and bearing wear; and cylinder bore surface finish effect on piston ring wear and sealing.

It is especially important for the engine designer to understand the limitations imposed on the design by the need to produce the engine on a transfer line using fixed tooling. While the fixed tooling is imperative for controlling costs and quality in high volume production it makes later design changes difficult and expensive. External dimensions such as the width of the cylinder block at the pan rails, or the deck height might be impossible to later increase as the revised part may not "fit" the machining line. As another example, moving a single drilling even a slight amount will be very expensive. The drilling is not made using an individual drill head but with a gear box holding many drill heads that simultaneously drill each of the holes on the particular surface of the part. Moving one drilling will involve modifying or replacing the entire gear box.

Certainly of interest to the engine designer is the ability of each machine to meet the tolerance specifications required for optimal engine performance and durability. There are key tradeoffs between what tolerance can be maintained in production, and the cost of the engine. Interchangeability of parts is key to mass production, and the design must be robust at the limits of the tolerance. A random sampling of the machined parts is used to determine the process standard deviation, and from that the process capability is calculated as the number of standard deviations that fit within the tolerance band of upper specification limit (USL) to lower specification limit (LSL), as shown in Fig. 7.11. The higher the number of standard deviations that can be fit within the tolerance band, the lower chance of a defect reaching a customer as illustrated in Table 7.3. Process capability is described by C_p (width of distribution with relation to the tolerance band), and C_{pk} (width, plus centering of the mean with relation to the tolerance band).

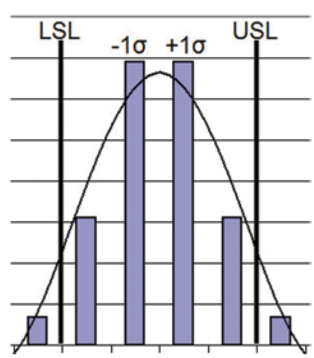

Fig. 7.11 Number of standard deviations between tolerance band

Table 7.3 Comparison of process capability (normally distributed)

Sigma level	Process capability index (Cp)	% of accurate parts produced by process	% of inaccurate parts produced by process	Defects per million parts produced
$\pm 1\sigma$	0.33	31.7	68.3	690,000
$\pm 3\sigma$	1.00	93.3	6.7	66,800
$\pm 6\sigma$	2.00	99.99966	0.00034	3.4

7.5 Recommendations for Further Reading

The following reference provides an overview of casting technology, including design guidelines. It is not specific to engines, and does not cover processes such as lost foam or the Cosworth process, but provides coverage of sand casting, permanent mold and die casting (see Gervin 1995).

The papers listed below address the design of cylinder blocks for aluminum die casting (see Takami et al. 2000; Kurita et al. 2004; Yamazaki et al. 2004).

The following paper describes a composite block design using magnesium and aluminum for an in-line six cylinder automobile engine. It is followed by a study in which a production aluminum block is modified for magnesium casting, and a multi-company summary of magnesium block casting development (see Baril et al. 2004; Powell et al. 2004; Pedersen et al. 2006).

The following paper describes the use of compacted graphite for a bedplate. The second paper below presents a recent update on the use of compacted graphite for engines (see Warrick et al. 1999; Dawson 2011).

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