MCE 451: Automobile Systems Design

LECTURE 2

2.0 CYLINDER BLOCK

The engine cylinder block is the main framework of a vehicle's engine which supports and holds other engine components. The cylinder block could come detached from the crankcase (assembled) (as seen in air- cooled engines) or integrated with the crankcase (integral) (as seen in water cooled engines) as shown in figures (3a) and (3b) respectively.

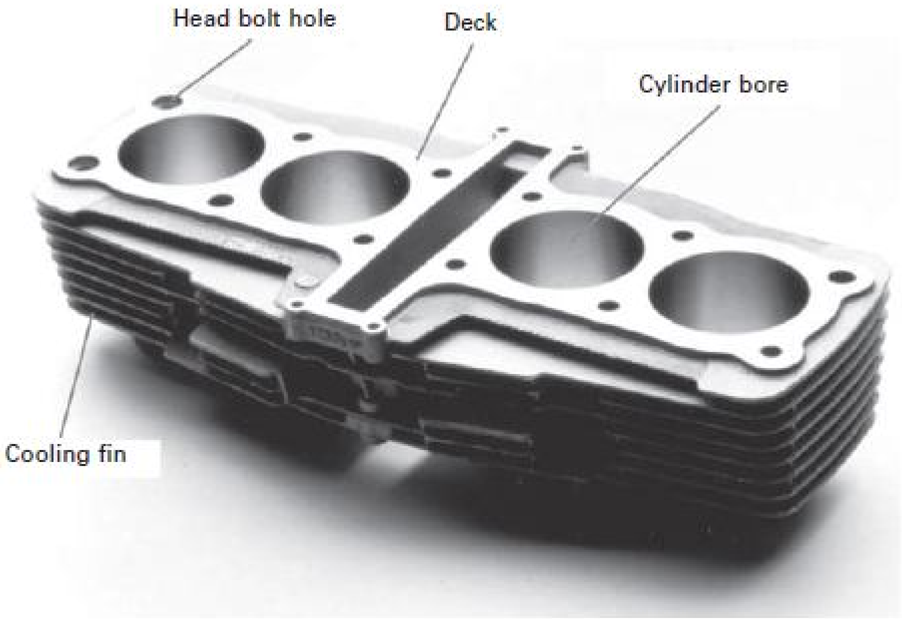


Figure 3(a):Air-cooled engine block

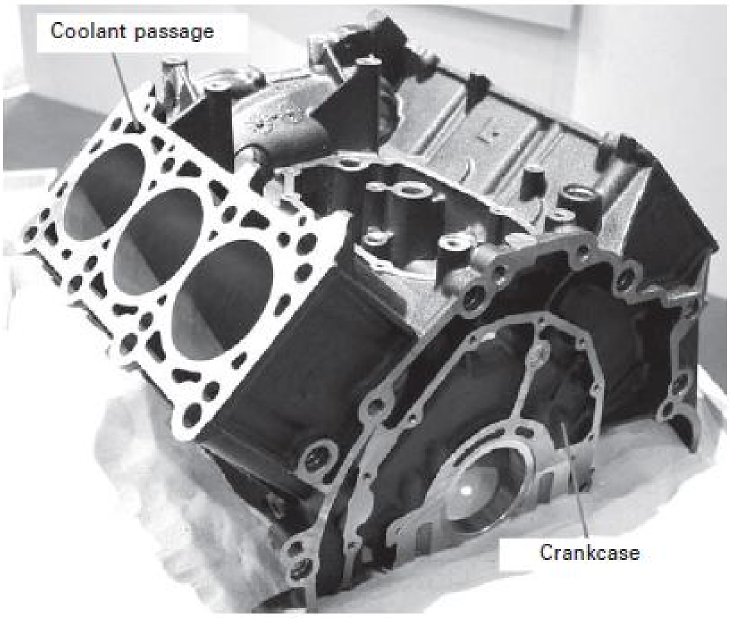


Figure 3(b): A cast iron cylinder block integrated with the crankcase

2.1 THE FUNCTION OF A CYLINDER BLOCK

The function and operation of an engine cylinder is summarized with the chart in figure 4.

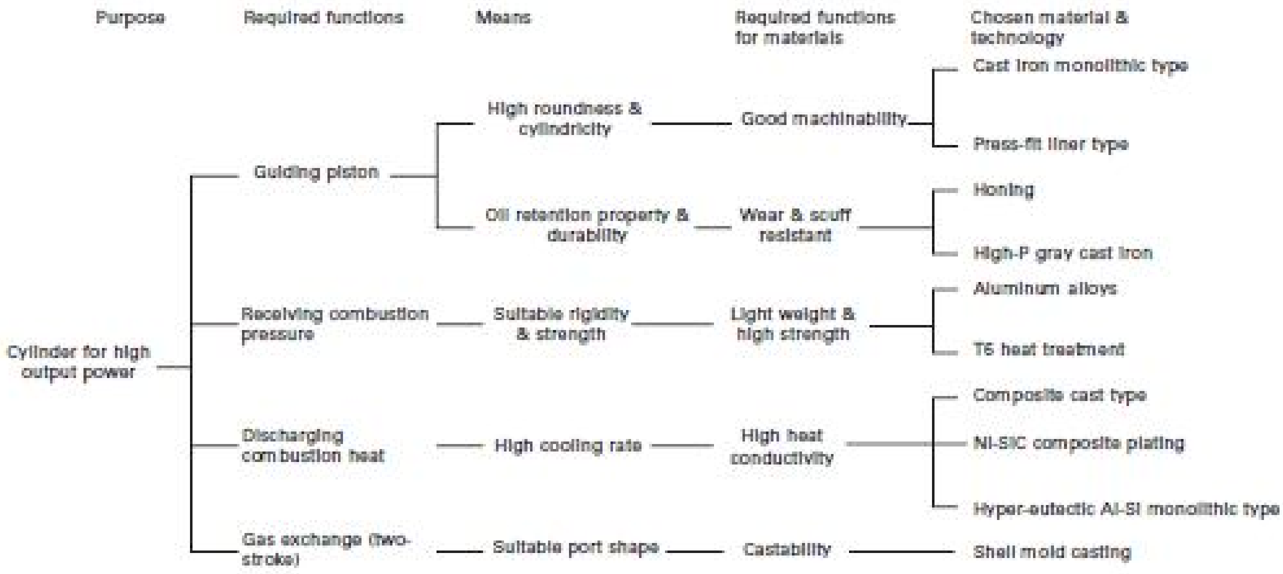


Figure 4: Functions of an engine cylinder

To minimize the wear at the top-dead-center region of the cylinder (which is as a result of insufficient oil film at the point), and scratch along the direction of travel of the piston, the engine cylinder is required to maintain accurate roundness and straightness in a tolerance order of micro-meters (µm) during operation. The wear on the cylinder walls as a result of the scratch along the direction of piston travel leads to increased blow-by and oil consumption.

Generation of higher power output from an engine translates to generation of more heat in the engine and this requires a higher cooling unit/system compared to a lower power output engine. While the cooling of an engine could be done with air or water, the air cooled engines come with simpler designs compared to the water cooled engines due to the absence of water passages in the engine block.

The use of air-cooled engines in automotive engines have been observed to be less efficient with increase in engine power output requirement and this has resulted in the switch of most automotive engines to water cooled engines. In summary, it could be said that the required cooling level of an engine determines the structure of its cylinder.

The chart in figure 5 shows the different types of cylinder block structures.

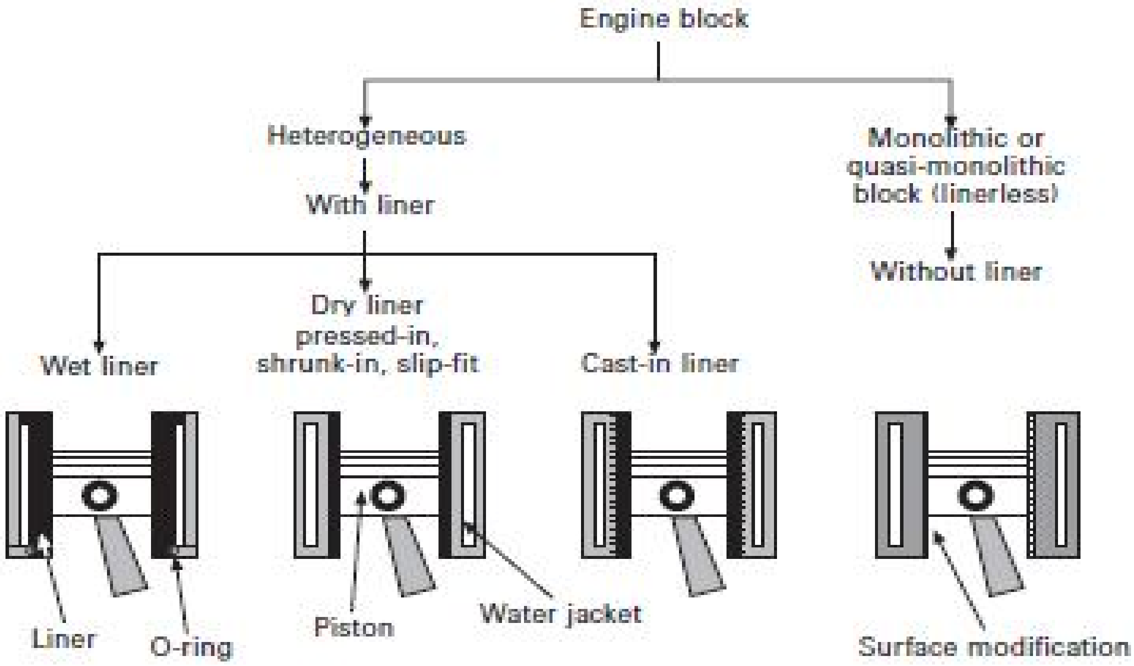


Figure 5: Bore design in engine blocks

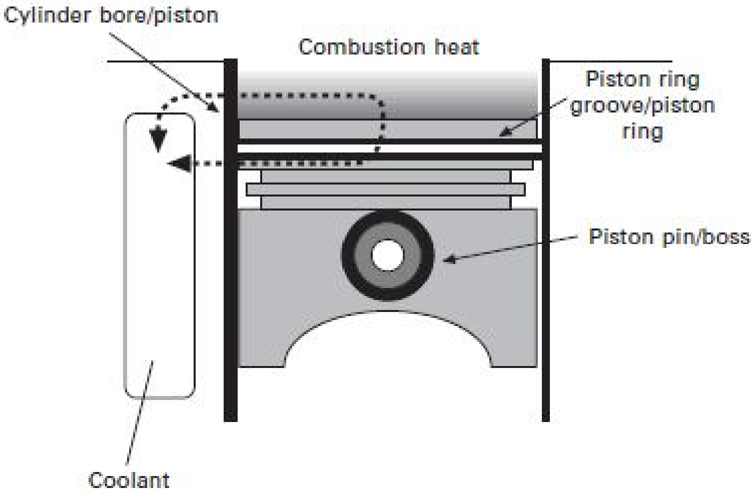


Figure 6: The Tribological System around a Cylinder Bore (black portions)

The monolithic or quasi-monolithic block are blocks made of one material. They are also known as a linerless block because they don’t have liners. The walls of the cylinder bore are either made of the same material as the block or a modified surface such as plating to improve the wear resistance of the surface. The linerless designs in multi-bore engines make the engines more compact by decreasing inter-bore spacing. The heterogeneous block are engines blocks with liners and a liner is also known as or called a **sleeve**. A **wet liner** is directly exposed to coolant at its outer surface and the heat on the engine cylinder wall is dissipated directly into the coolant. The wet liner normally has a flange at the top and the clamping action of the cylinder head presses the liner into position. A rubber or a copper O-ring is used at the bottom and on some occasions, at the top of a wet liner to prevent the leakage of the coolant into the crankcase. Compared to the dry liner, the wet liner is made thicker because of its requirement to withstand combustion pressure and heat without the added support of the engine block. The dry liner presses or shrinks into a cylinder that has already been bored. The dry liner is thinner compared to the wet liner and has no direct contact with the coolant. In the cast-in liner design, the cast is introduced and encloses the liner during the casting process of the entire cylinder block.

Cylinder blocks are basically made of cast iron or aluminium alloy. Aluminium engine blocks are much lighter compared to cast iron blocks.

2.2 LINER DESIGN

Liner or sleeve is a part of the components that make up an automotive engine and to avoid the failure of this engine part, proper design is required. During the operation of an engine, the liner or sleeve, whether wet or dry is subjected to gas pressure from the compressed and expanding gas and the side thrust from the piston.

The gas pressure in the combustion chamber produces majorly two (2) types of stresses:

(i) The longitudinal stress and

(ii) The circumferential stress

It should be noted that the two types of stresses are orthogonal to each other and this makes the net stress in each direction reduced.

The apparent longitudinal stress is expressed as

$$P_L = \frac{Force}{Area} = \frac{\pi \times r^2 \times P_{\max}}{\pi (r_o^2 - r^2)} = \frac{r^2 \times P_{\max}}{(r_o^2 - r^2)}$$

While apparent circumferential stress is expressed as

$$P_c = \frac{Force}{Area} = \frac{\pi \times r \times S \times P_{\max}}{t \times S} = \frac{r \times P_{\max}}{t}$$

Where,

r_o = Outside radius of the liner

r = Inside radius of the liner

$P_{\max}$ = Maximum pressure in the liner

$t =$ The liner thickness

$S =$ The length of the cylinder

m = Inverse of the Poisson's ratio (m is usually taken as 4)

Note: $P_{\max}$ is taken to be nine (9) to ten (10) times the indicated mean effective pressure of a cylinder.

The net longitudinal stress $P_{Lnet} = P_L - \frac{P_c}{m}$

The net circumferential stress $P_{cnet} = P_c - \frac{P_L}{m}$

The thickness of the liner (t) is usually determined using the expression for thickness calculation in a thin wall cylinder.

$$t = \frac{P_{\max} \times r}{P_c} + D_{rebor}$$

Where D_{rebor} = Reboring allowance

r (mm)	37.5	50	75	100	125	150	175	200	225	250
D_{rebor} (mm)	1.5	2.4	4.0	6.3	8.0	9.5	11.0	12.5	12.5	12.5

The wet liner thickness can also be obtained with the empirical relation, given as:

$$t = 0.09r + 1.6mm$$

The thickness of a dry liner is given as:

$$t = 0.06r \text{ or } t = 0.07r$$

The thickness of the water jacket wall is given as:

$$t = 0.064r + 1.6mm$$

Note: The allowance of 1.6 mm or $\frac{t}{3m}$ is used for bigger cylinders and $\frac{3t}{4}$ is used for smaller cylinder.

The empirical relation for water jacket space, that is, the space or opening (width) between the outer liner wall and the inner water jacket wall, is given as:

$$W_{jacket} = 0.16r + 6.5mm$$

The water passage space of 10mm is usually used in small to medium engines.

2.3 Engine Performance

The performance of an engine is determined by a lot of factors. The factors considered include: (i) indicated power (ip) (ii) brake power (bp) (iii) friction power (fp) (iv) indicated and brake mean effective pressures (mep) (v) mechanical and thermal efficiencies (vi) fuel consumption (specific fuel consumption) (vii) volumetric efficiency. The performance of an engine can be determined if the characteristics or parameters of the engine can be evaluated. The engine parameters may be obtained by the measurement of the engines quantities and the results plotted graphically in the form of performance curve.

2.3.1 Indicated Power

Indicated power can be defined as the rate of work done by the combusting charge on the piston as evaluated from the indicator diagram obtained from the engine. If the cross-sectional area of a piston is given as A and the expanding combusting charge in the engine cylinder exerts a pressure P on the piston's cross sectional area A, the total force exerted on the piston is given as: Force F = P.A (N).

Assuming the pressure exerted on the piston remains constant and the piston is forced through a distance L which is equal to 1 meter.

The work done W = FL = PaL.

If the piston makes n working strokes per second, then the work done per second is given as:

Power Developed = PLAn (W)

In real engine operation, the engine cylinder pressure is not constant throughout the cycle. The mean effective pressure of the engine cylinder is calculated and used as P. The power calculated from the in-cylinder engine pressure is called the indicated power.

Indicated Power (ip) = PLAn (W) or PLAn $*10^{-3}$ (KW).

The number of firing strokes per second in an engine is expressed as n while N represents the engine speed per second.

For a two-stroke engine n = N

For a four-stroke engine n = N/2

For a double acting engine n = 2N

2.3.2 Brake Power

The power available at the piston is the indicated power and it is measured by the indicator diagram. The useful power finally generated by the engine (available to the crankshaft) is lower than the indicated power because of the power used to overcome friction at the bearings and sliding parts.

The power output of the engine available to the engine crankshaft is known as the brake power or shaftpower. It is called brake power because it is measured by a brake at the crankshaft.

The difference between the indicated power and brake power is known as the friction power of the engine.

Friction Power fp = ip – bp

2.3.3 Mechanical Efficiency

The mechanical efficiency of an engine is defined as the ratio of the power available to the crankshaft to the power available at the piston i.e. the ratio of engine brake power to the indicated power.

Mechanical Efficiency $\eta_{th} = \frac{bp}{ip}$

QUESTION 1

If the indicated power of a diesel engine running at 4200rpm is 45.82 kW; given that the Mean Effective Pressure is 540kN/m^2 and the engine bore is 70 mm. The engine works on a four-stroke cycle and has 6 cylinders. Calculate the engine stroke.

Solution

For the six cylinders, the indicated power developed = 6 X 7.637 = 45.82 KW.

$$IP = \frac{P_i LAn}{1000}$$

$$L = \frac{IP \times 1000}{P_i An}$$

$$= \frac{45.82 \times 1000 \times 4}{540 \times 1000 \times \pi \times 0.07^2 \times 35 \times 6} = 0.105m$$

QUESTION 2

A compression ignition engine has a piston area of 0.00785m^2, stroke of 0.12m and an indicated mean effective pressure of 500kN/m^2. Calculate the bore and indicated power at the crank-speed of 3600 rpm. If the mechanical efficiency of this load and speed is 84%, compute the brake power output and the power lost from friction. The engine operates on a two-stroke cycle

Solution

Area of piston A = $\frac{\pi d^2}{4}$

The Bore $d = \sqrt{\frac{A \times 4}{\pi}} = \sqrt{\frac{0.00785 \times 4}{\pi}}$ = 0.1m

The indicated power (ip) = $\frac{500000 \times 0.12 \times 0.00785 \times 3600}{1000 \times 60}$ = 28.2 KW

The brake power (bp) = ip X η_{th} = 28.2 (0.84) = 23.7 KW

Friction power (fp) = 28.2 – 23.7 = 4.5 KW

2.4 Cylinder Head Design

An engine cylinder head is a detachable engine component that make part of the combustion chamber and it is a component of the engine that accommodates, the intake and exhaust valves, the spark plug (S.I. engine), injector nozzle (for a diesel engine)and ports for the passage of air and fuel or air alone.

For this design purpose, the cylinder head is taken to be approximately a flat circular plat whose thickness (t_{ch}) can be determined with the expression below:

Cylinder head thickness $t_{ch} = 2r\sqrt{\frac{C \times P_{\max}}{P_{cnet}}}$

r = Inside radius of the liner

$P_{\max}$ = Maximum pressure in the liner

C = is a design constant taken as 0.1

P_{cnet} = The net circumferential stress. The values used range from 30 to 100MPa

QUESTION 3

A compression ignition engine has a piston area of 0.00785m^2, stroke of 0.12m and an indicated mean effective pressure of 500kN/m^2. Calculate the bore and indicated power at the crank-speed of 3600 rpm. If the mechanical efficiency of this load and speed is 84%, compute the brake power output and the power lost from friction. The engine operates on a two-stroke cycle

Calculate the liner thickness (t) and the cylinder head thickness (t_{ch}). Take the net circumferential stress $P_{cnet} = 42 N/mm^2$

Note: The liner is a dry liner

Solution

Recall r = 0.05m

For a dry liner the thickness is given as $t = 0.07r$

The thickness of the liner (t) = 0.07*0.05 = 0.0035m = 3.5 mm

The external diameter of the liner is D_0 = 2r + 2*t = 2(0.05) + 2(0.0035) = 0.107 m or 107mm

Maximum cylinder pressure $P_{\max} = 10P_i$ = 10(500) = 5MN/m^2

Cylinder head thickness

$$t_{ch} = 2r\sqrt{\frac{C \times P_{\max}}{P_{cnet}}} = 2 \times 0.05\sqrt{\frac{0.1 \times 5 \times 10^6}{42 \times 10^6}} = 0.0109m = 10mm$$

2.5 ENGINE BLOCK MATERIALS AND ITS PRODUCTION PROCESSES

2.5 THE CAST IRON MONOLITHIC BLOCK

The widespread use of cast iron monolithic block is as a result of its low cost and its formidability. This type of block normally comes as the integral type where the engine cylinder and the upper crankcase are joined together as one. The iron used for this block is the gray cast iron having a pearlite-microstructure. The iron is called gray cast iron because its fracture has a gray appearance. Ferrite in the microstructure of the bore wall should be avoided because too much soft ferrite tends to cause scratching, thus increasing blow-by.

The production of cast iron blocks using a steel die is rear because its lifecycle is shortened as a result of the repeated heat cycles caused by the molten iron. Sand casting is the method widely used in the production of cast iron blocks. This involves making the mould for the cast iron block with sand. The preparation of sand and the bonding are a critical and very often rate-controlling step. Permanent patterns are used to make sand molds. Usually, an automated molding machine installs the patterns and prepares many molds in the same shape. Molten metal is poured immediately into the mold, giving this process very high productivity. After solidification, the mold is destroyed and the inner sand is shaken out of the block. The sand is then reusable. The bonding of sand is done using two main methods: (i) the green sand mold and (ii) the dry sand mold.

A green sand mold consists of mixtures of sand, clay and moisture. The dry sand mold consists of sand and synthetic binders cured thermally or chemically.

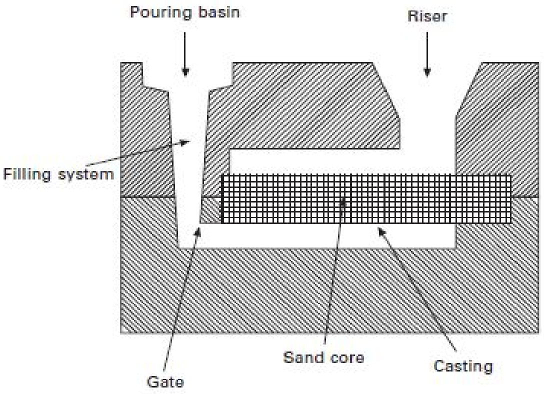


Figure 7: Sand mold with a sand core

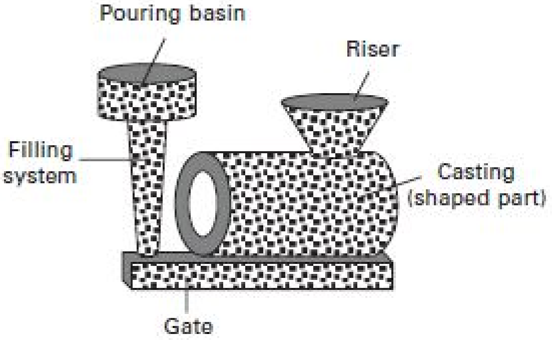
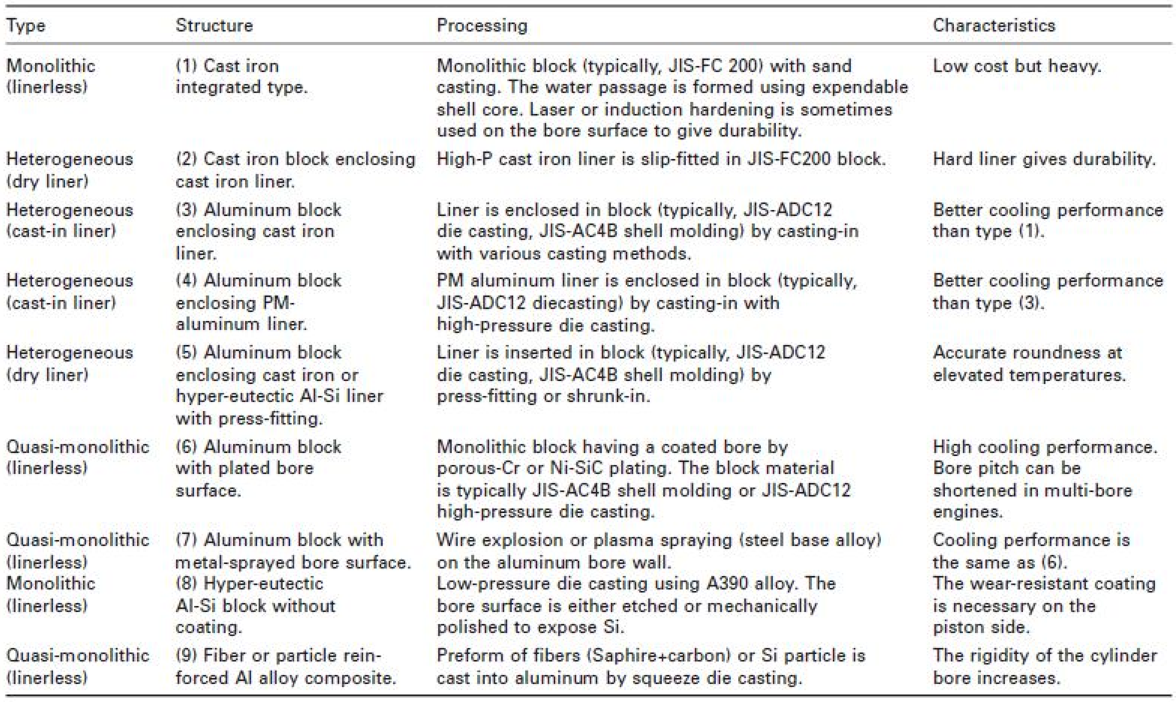


Figure 8: Cylindrical casting obtained using the mold shown in figure 7.

Figure 7 shows a schematic view of a sand mold used to shape a tube. This mold includes a sand core to make the tube hollow. The casting obtained from using this mold shown in figure 7 is shown in figure 8. Usually, molten iron in a ladle is gently poured into the cavity under the force of gravity using a filling system. The sand core forming an inside hollow shape is made from a dry sand component. The bore as well as the coolant passages in the cylinder block is shaped as cored holes.

Table 2: Engine cylinder types, structures, processing methods and characteristics



Type	Structure	Processing	Characteristics
Monolithic (linerless)	(1) Cast iron integrated type.	Monolithic block (typically, JIS-FC 200) with sand casting. The water passage is formed using expendable shell core. Laser or induction hardening is sometimes used on the bore surface to give durability.	Low cost but heavy.
Heterogeneous (dry liner)	(2) Cast iron block enclosing cast iron liner.	High-P cast iron liner is slip-fitted in JIS-FC200 block.	Hard liner gives durability.
Heterogeneous (cast-in liner)	(3) Aluminum block enclosing cast iron liner.	Liner is enclosed in block (typically, JIS-ADC12 die casting, JIS-AC4B shell molding) by casting-in with various casting methods.	Better cooling performance than type (1).
Heterogeneous (cast-in liner)	(4) Aluminum block enclosing PM-aluminum liner.	PM aluminum liner is enclosed in block (typically, JIS-ADC12 diecasting) by casting-in with high-pressure die casting.	Better cooling performance than type (3).
Heterogeneous (dry liner)	(5) Aluminum block enclosing cast iron or hyper-eutectic Al-Si liner with press-fitting.	Liner is inserted in block (typically, JIS-ADC12 die casting, JIS-AC4B shell molding) by press-fitting or shrunk-in.	Accurate roundness at elevated temperatures.
Quasi-monolithic (linerless)	(6) Aluminum block with plated bore surface.	Monolithic block having a coated bore by porous-Cr or Ni-SiC plating. The block material is typically JIS-AC4B shell molding or JIS-ADC12 high-pressure die casting.	High cooling performance. Bore pitch can be shortened in multi-bore engines.
Quasi-monolithic (linerless)	(7) Aluminum block with metal-sprayed bore surface.	Wire explosion or plasma spraying (steel base alloy) on the aluminum bore wall.	Cooling performance is the same as (6).
Monolithic (linerless)	(8) Hyper-eutectic Al-Si block without coating.	Low-pressure die casting using A390 alloy. The bore surface is either etched or mechanically polished to expose Si.	The wear-resistant coating is necessary on the piston side.
Quasi-monolithic (linerless)	(9) Fiber or particle reinforced Al alloy composite.	Preform of fibers (Saphire+carbon) or Si particle is cast into aluminum by squeeze die casting.	The rigidity of the cylinder bore increases.

Note: PM means Powder Metallurgy (Powder Metallurgy Aluminium)

Cast iron has successfully been used for making monolithic blocks. This is as a result of the advantage of mass-producing large complex shapes through its casting process. For the efficient performance of an engine cylinder, the cylinder bore must have high dimensional accuracy. A finishing process called honing is used to give accurate roundness and straightness to the cylinder bore. The whetstone grinds the bore by exerting an expanding pressure. The vertical motion of the head together with revolution generates the crosshatch pattern and the profile of the crosshatch pattern is determined by the sharpness of the whetstone .The figure in figure 9 shows a micrograph of a honed cylinder surface. The honing whetstone carved the crosshatch pattern. The grooves of the crosshatch hold the lubricating oil during engine operation. The resulting oil film on the surface of the cylinder generates hydrodynamic lubrication.

A finished surface of the engine bore exposes the graphite without burr. The quality of the honing is measured by surface roughness value. The graphite in the cast iron block surface works as a lubricant during machining as well as during the engine operation. The lubrication offered by graphite on the wall surface reduces the frictional force between the wall and the contacting surfaces. Some solid lubricants known are Sn, Pb, Graphite, MoS_2

(Molybdenum disulfide), WS_2 (Tungsten disulfide) etc. The low frictional force of graphite comes from the fact that the crystal structure has a very low frictional coefficient during slip at the basal plane. The graphite decreases friction for tools during machining. The brittle nature of graphite makes chips discontinuous. The resultant high machinability gives high dimensional accuracy to cast iron parts. The graphite also works as a solid lubricant to prevent seizure of the piston or piston rings even under less oily conditions.

The micro-burr of the crosshatch disrupts the oil film to obstruct hydrodynamic lubrication. Additional Mn-phosphate conversion coating chemically removes the micro-burr to increase oil retention. This prevents seizure during the running-in stage. As well as a dimensional accuracy, the surface profile also determines oil retention which, in turn, greatly influences wear resistance.

Figure 9: Cross pattern of a cylinder surface after honing

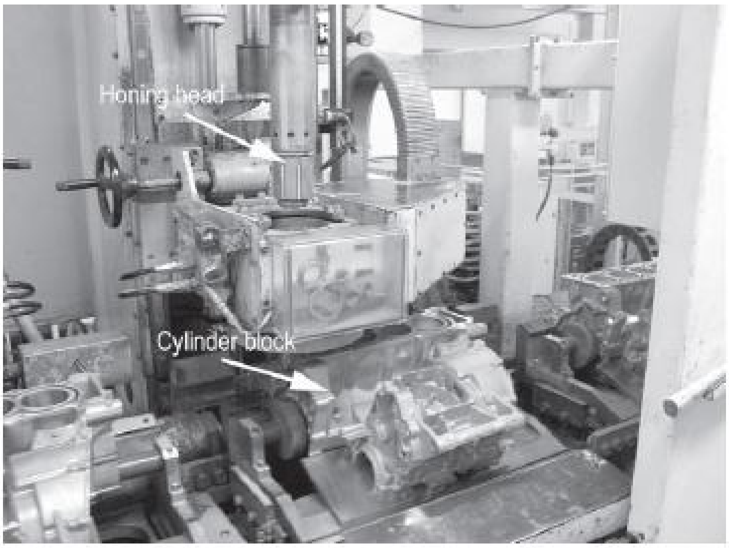


Figure 10: Honing operation being performed on an engine block

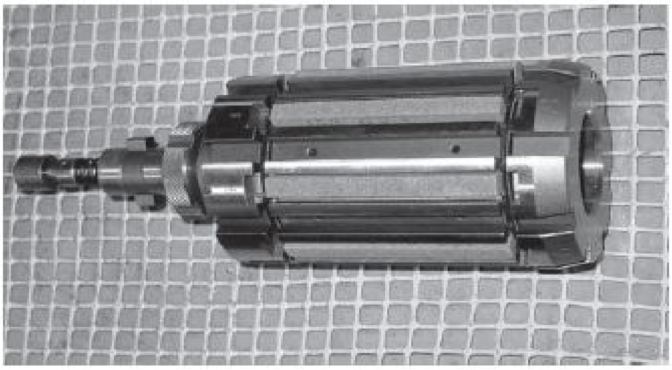


Figure 11: Honing tool head

2.5.1 Improvement of Wear Resistance of Cast Iron Blocks

In a four-stroke engine, oil is splashed on the cylinder wall for lubrication and cooling. Because of the need to scrape of excess oil, the oil control ring contact pressure is set high. To increase the durability of the bore, since the bore is expected to have high wear resistance, a hard gray cast iron containing phosphorus (P) is often used. The increased P crystallizes from the melting stage, as hard steadite having a chemical composition of Fe_3P. This alloy composition has good wear resistance because of high hardness but low machinability. It is usually employed in wet and dry liners in a cast iron block or aluminium block and not used in the making of the entire engine block.

The commercial diesel engine is required to cover a mileage of 1,000,000 km during its service life and high temperature of operation/combustion, which is typical of such engines. The bore of these engines require additional heat treatment processes on the bores surface. To achieve this, a nitride liner is often enclosed to increase hardness. A phosphate conversion coating on the liner also prevents corrosion. Alternatively, instead of enclosing a hard liner, interrupted quench hardening by laser or induction heating can be applied to the bore wall of a monolithic cast iron block.

2.6 ALUMINIUM BLOCK

Aluminium block has a weight about 40% less than a cast iron engine block and this helps in the reduction of fuel consumption in vehicles with aluminium blocks. The thermal conductivity of aluminium alloy used in making the engine block is 150 W/(m.K) while that of the cast iron is about 50 W/(m.K). This gives aluminium alloy high cooling performance at a lower weight. However, aluminium alloy is soft and the wear resistance is generally low. To deal with this problem, aluminium alloy blocks with enclosed iron liners (normally cast iron) are widely used.

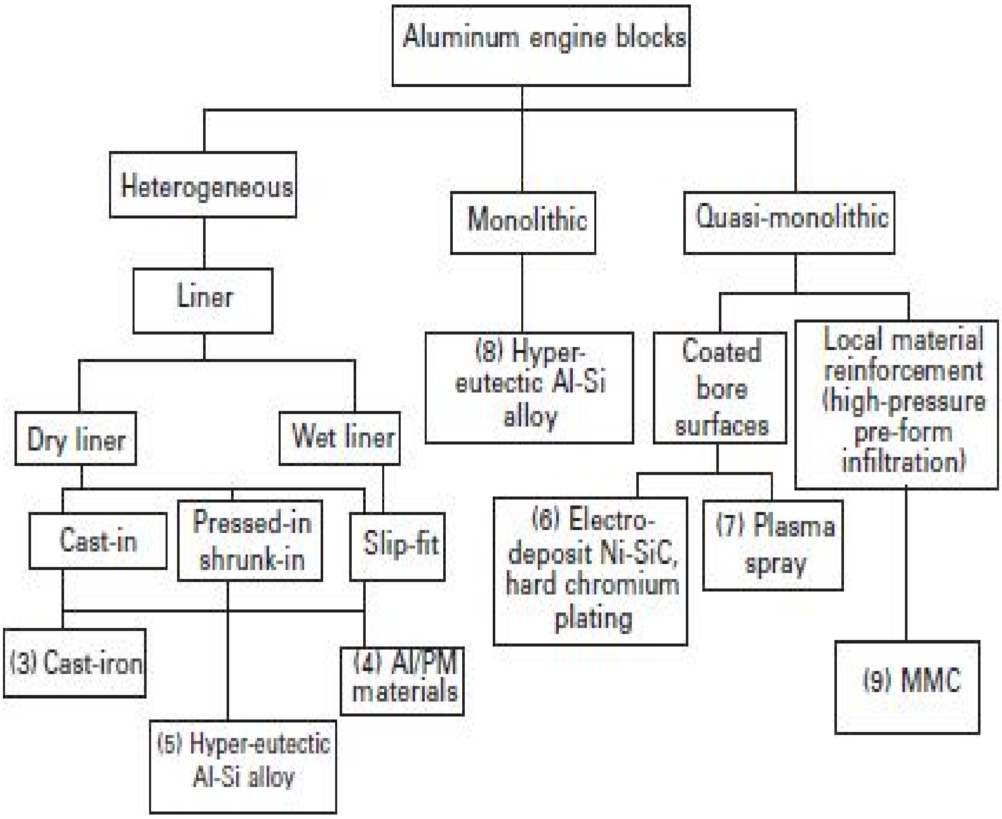


Figure 12: Aluminium Engine Block Design

Figure 13: Cast Iron Liner having a Dimpled Outer Surface

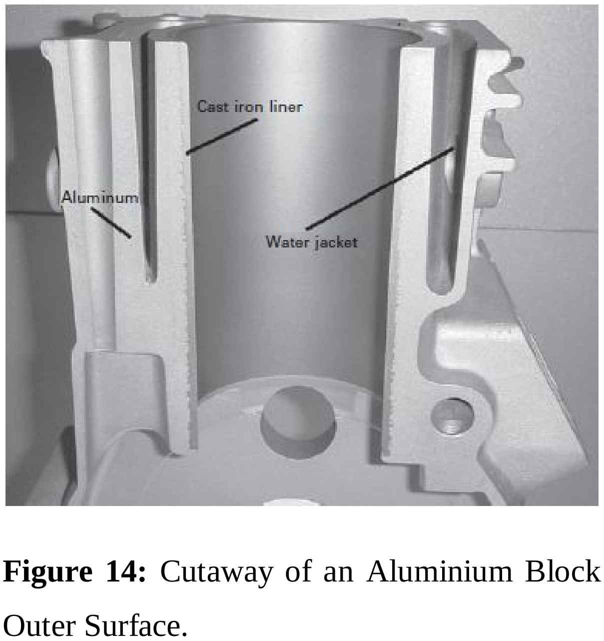


Figure 14: Cutaway of an Aluminium Block Enclosing a Cast Iron Liner having Dimpled Outer Surface.

The dimples in the outer surface of the liner are caused by the coarse sand particles of the mold. The dimple gives an excellent heat transfer property with its large surface area and close contact. An alternative method has been proposed: coating the outside surface of a cast iron liner with aluminium creates good metallurgical continuity with the aluminium block. The coated layer works as a binding layer between the liner and the block’s aluminium. A direct dip of the cast iron liner into molten Al-SI alloy or thermal spray of Al-Si alloy on the liner is used for the coating.