ENGINE BLOCK MATERIALS AND ITS PRODUCTION PROCESSES

2.2 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.

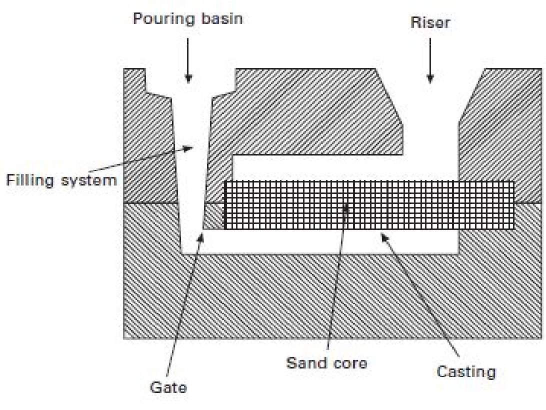

Figure 7: Sand mold with a sand core

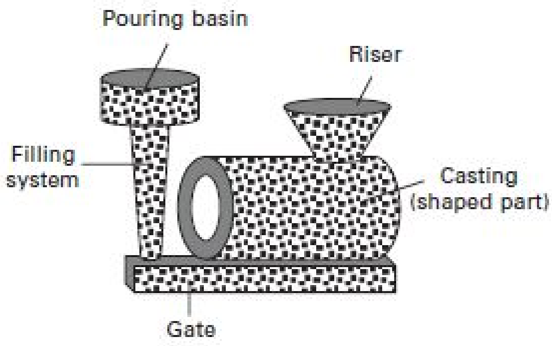

Figure 8: Cylindrical casting obtained using the mold shown in figure 7.

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 rein-forced 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 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

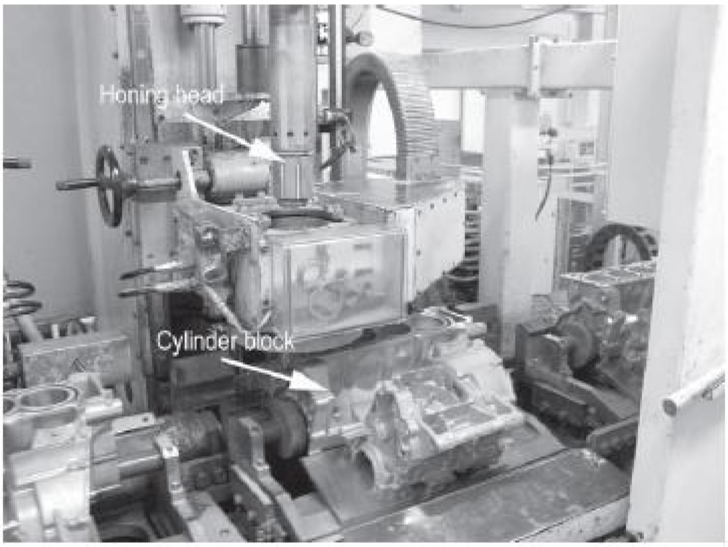

Figure 10: Honing operation being performed on an engine block

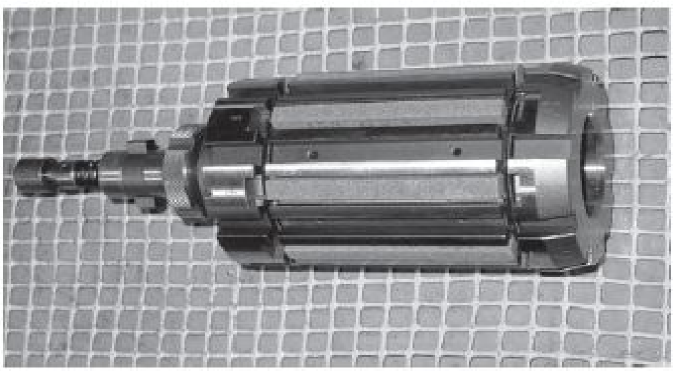

Figure 11: Honing tool head

2.2.1 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 melt as hard steadite having a chemical composition of Fe_3P. The curious shape of the steadite stems from its low freezing point. The iron crystal solidifies first then the residual liquid solidifies to form steadite in the space between the iron crystals. 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 1000,000 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.

2.3 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.

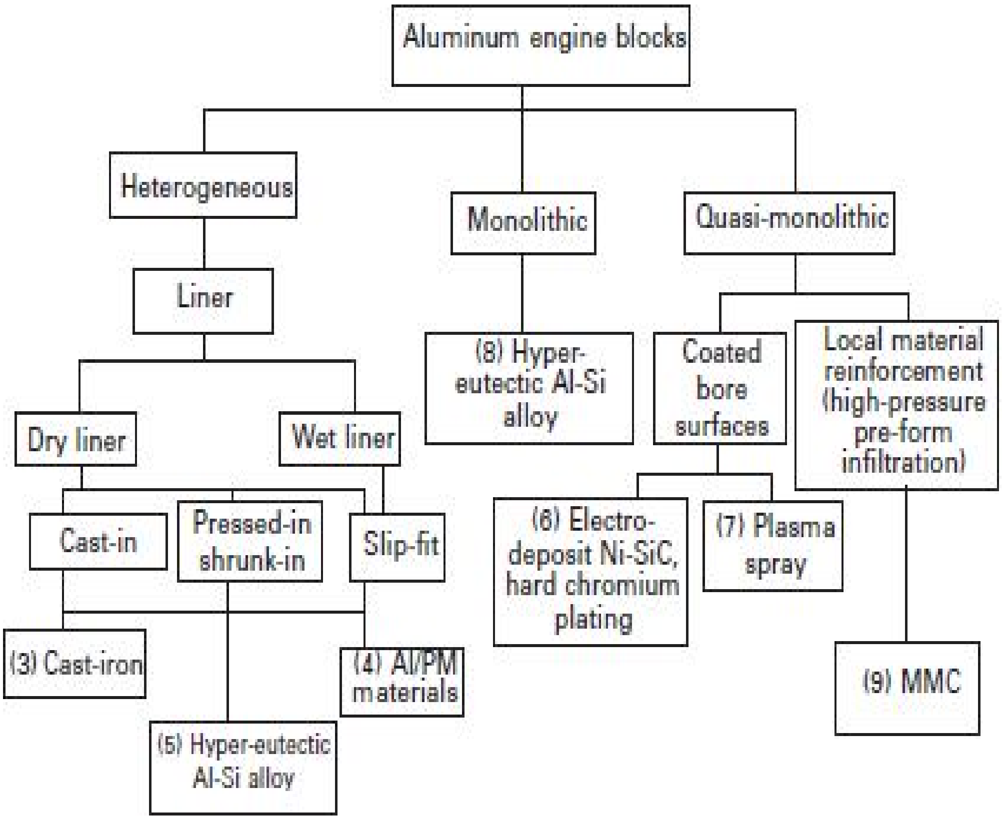

Figure 12: Aluminium Engine Block Design

Figure 13: Cast Iron Liner having a Dimpled Outer Surface

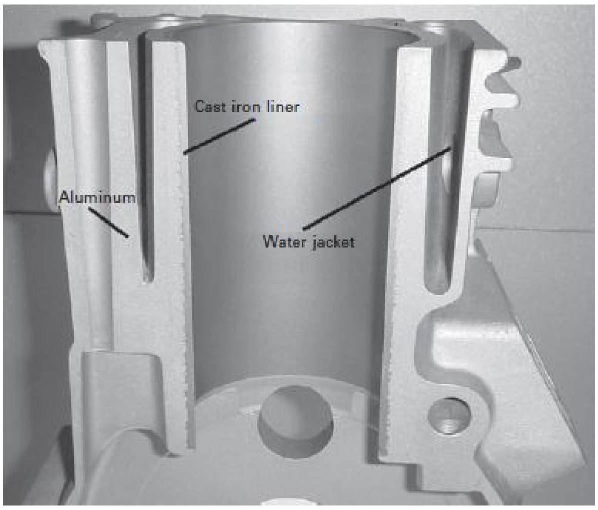

Figure 14: Cutaway of an Aluminium Block Enclosing a Cast Iron Liner having Dimpled Outer Surface.

The dimples in the outer surface of the liner is 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.

2.3.1 THERMAL DISTORTION AND HEAT DISCHARGE

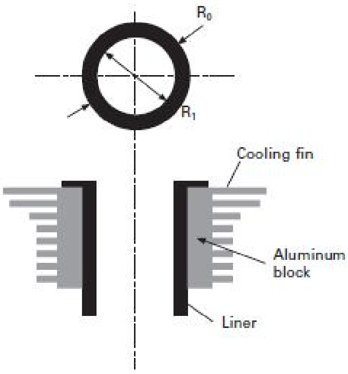

Figure 16: Press-fit liner structure

The liner as shown in the figure above is enclosed by either a press-fit or shrunk-in process. The press-fitted liner is a simple flanged tube. The liner should be perfectly finished before fitting. The finishing process includes grinding of the outside surface and honing of the inside bore wall. In some cases, honing of the inside bore is done after fitting.

If the liner is inserted into the cylinder body without further treatment, it unfastens as a result of the thermal expansion of aluminium. The correct design enables the bore to retain a perfectly round form when the liner elastically expands under the thermal expansion of the aluminium body. The external diameter of the liner shrinks forms R_0 before fitting to R_1 after fitting. The interference ($=R_0 - R_1$) should be such that it does not cause buckling of the liner but, at the same time, provides a sufficient tightening force even at elevated temperatures. It is usually around 60 µm for a 60mm bore i.e. (1/1000) of the bore.

The shrunk-in process is also used. It fastens the liner together by heating the outer block until it expands sufficiently to pass over the liner diameter and on cooling, grips it tightly. The shrunk-in design is widespread in outboard marine engines. Where a cast iron block is used, the liner is inserted and held without interference because both materials are the same. Unlike the composite cast design, individual liners can be replaced once they are worn. Hence, replacing the entire block is avoided.

2.3.2 POWDER METALLURGICAL ALUMINUM LINER IMPROVES HEAT TRANSFER

In a composite cast cylinder, the heat transfer through a cast iron liner is not that good. A thick liner reduces the heat conduction, raising the bore wall temperature. A hard aluminium liner has been proposed to deal with this problem. Honda has marketed a motorcycle engine using cylinder liners made from a rapidly solidified powder metallurgical (PM) aluminium alloy. The chemical composition of the liner is Al-17% Si-5 Fe- 3.5 Cu – 1 Mg – 0.5 Mn containing Al_2O_3 and graphite. The hard Si particles (1200HV) as well as finely dispersed intermetallic compounds embedded in the aluminium matrix give increased wear resistance. The liner is cast in by high-pressure die casting. The resulting wear resistance is nearly the same as that of cast iron. Daimler-Chrysler has also used a PM alloy cylinder liner in its car engine. It is cast in by high-pressure die casting. This process is considered to be far more cost effective and it avoids the difficulties in tribological control of the hyper-eutectic Al-Si block. This process used to achieve an optimal bore surface is almost the same as that used in producing a monolithic block of hyper-eutectic Al-Si alloy.

The molten alloy is sprayed and rapidly cooled into a powder first. The powder has a very fine microstructure during spraying. The powder is then canned in a vacuum to make a billet for extrusion. Finally, the heated billet is hot-extruded into a tube. A spray forming process that directly deposits the sprayed powder to form a billet shape is also used. The powder particles weld together to form a bulk material during extrusion. The extruded tube is then cut into liners. The process generates the hardness and wear resistance needed for a liner.

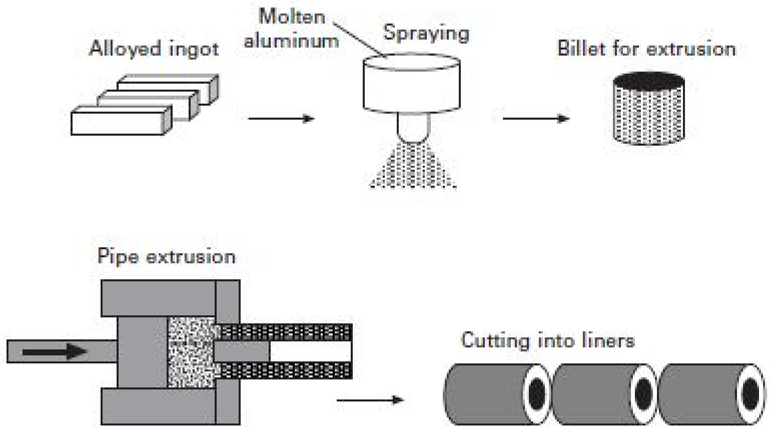

Figure 17: Manufacturing process of PM aluminium liner including spraying and extrusion.

2.4 IMPROVING ENGINE COMPACTION WITH SURFACE MODIFICATION

Shortening the Bore Interval

A low dimensional accuracy after machining or a thermal distortion during operation tends to cause poor clearance of the liner to the piston. Poor clearance removes necessary oil film, and at worst, can cause seizure. However, when the power output is not so high, the two-metal structure can lower the temperature sufficiently to maintain appropriate fluidity of the oil. The improved lubrication compensates for any poor clearance. This will be sufficient for an engine below about 100 HP a liter (74.5 kW/L) as a power output per unit displacement. However, at a higher power output range, this structure does not allow adequate cooling, due to the low thermal conductivity of the cast iron liner, and is likely to cause distortion. This problem can be addressed by redesigning the block.

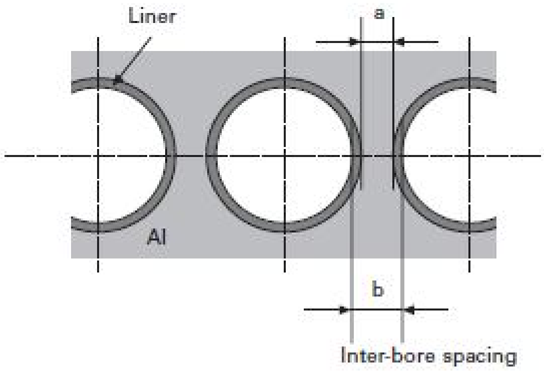

Figure18: Inter-bore spacing of a cylinder block enclosing liners. Adequate thickness (a) of the aluminium wall is necessary to hold the liner. The decreased inter-bore spacing (b) makes the engine compact.

Figure 18 illustrates the deck of a multi-cylinder block showing interbore spacing. The liner must have an appropriate wall thickness to keep its rigidity. If the liner does not have metallurgical continuity with aluminium, the required minimum thickness needs to be 2 mm. The jacket wall enclosing the liner also has to have enough thickness (a). As a general conclusion, these requirements cannot shorten the inter-bore spacing (b) to less than 8 mm.

Chromium plating

To make engines more compact, several linerless structures have been proposed. Monolithic and quasi-monolithic designs significantly decrease the bore wall temperature because of a higher heat transfer rate, generating less distortion. However, too narrow inter-bore spacing makes sealing by gasket difficult. A thin chromium layer directly plated onto an aluminium-alloy bore wall forms the running surface. The plated chromium shows good wear resistance because of its high hardness (800 HV). This process has been used since the invention of porous chromium plating by V Horst in 1942. It generates finely dispersed cracks in the chromium layer, as shown in Fig. 19. The cracks retain oil to generate hydrodynamic lubrication. The technology was first used in the reciprocating engine of an aeroplane but more recently sports car and motorcycle manufacturers have also used this technology. The technology does not require special surface treatment at the piston surface.

A steel liner plated with chromium has also been proposed as a dry liner for diesel engines. The plated chrome layer is, however, inferior in scuffing resistance. The disposal of waste fluid from the plating facility creates environmental problem. As an alternative, Ni-SiC composite plating is also used.

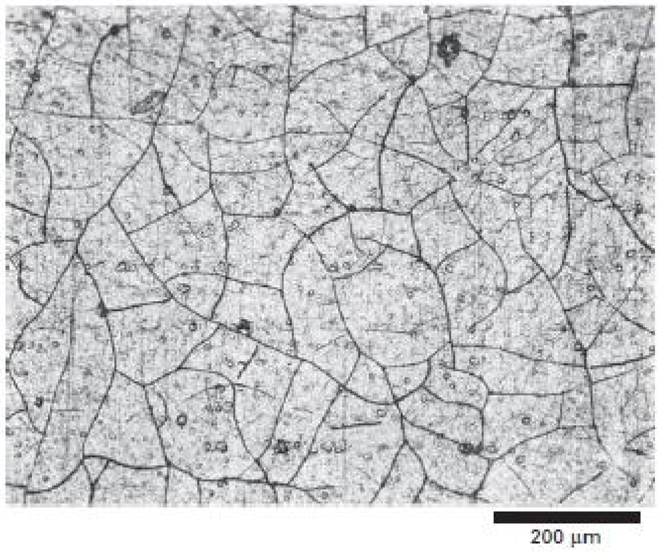

Figure 19: Micro-Cracks of Plated Cr Surface

Ni-SiC (Ni-Silicon Carbide) composite plating

This process generates a Ni layer dispersing SiC particles. Figure 20 shows a water-cooled cylinder block coated with this plating. The piston surface does not require a special coating to prevent scuffing.

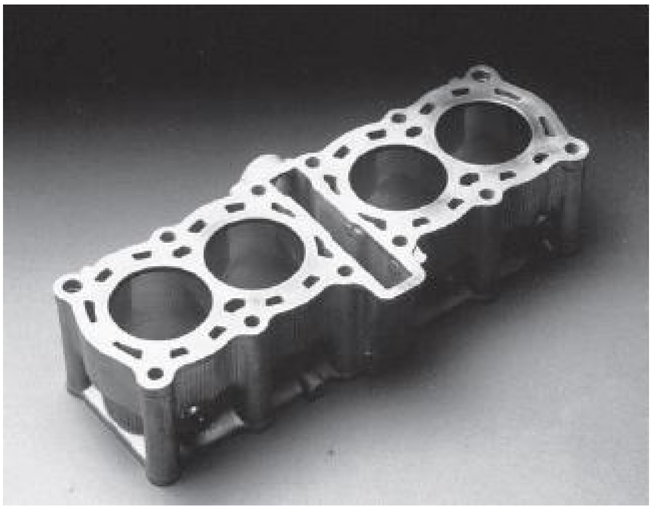

Figure 20: Water-Cooled Cylinder Block

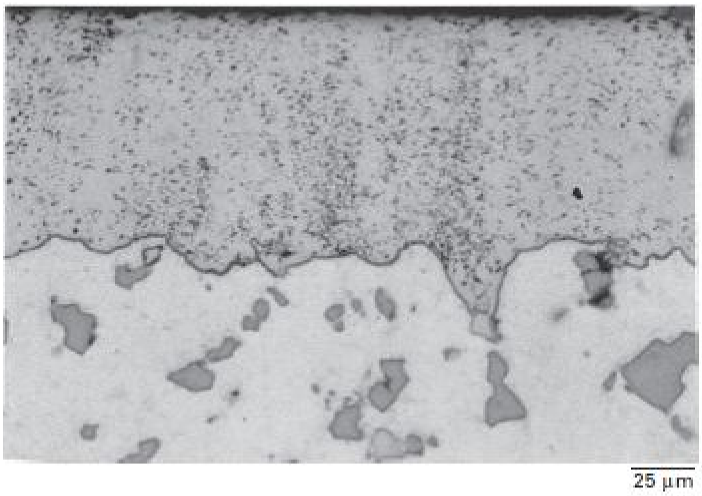

Figure 21: Microstructure of Ni-SiC Composite Plating on the Aluminium Bore.

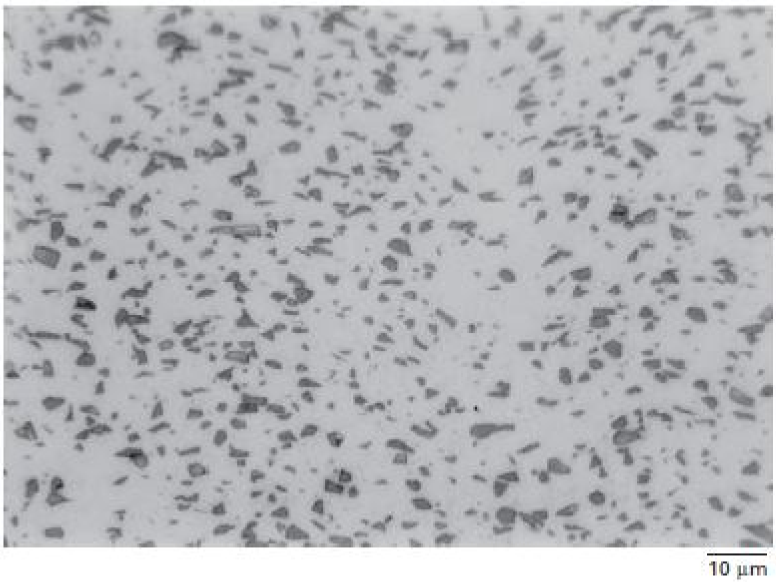

Figure 22: Magnified View of Dispersed SiC

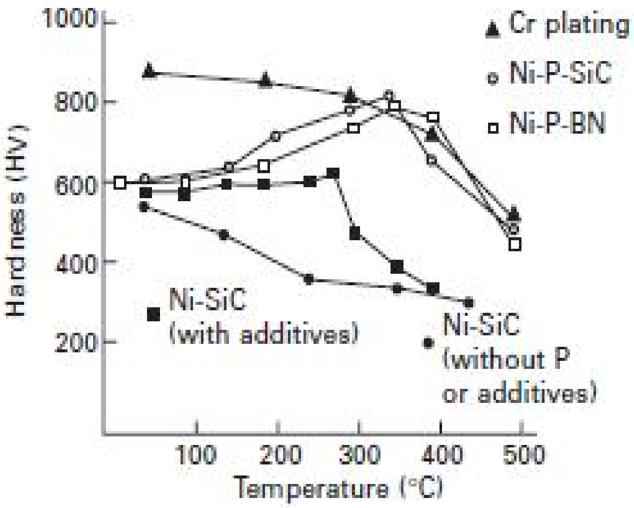

Figure 23: Hardness changes with heating. The measure is taken after holding the temperature of the substance in focus for one hour at the indicated temperature. The P added substances show higher hardness around 350 ˚C. The substance with BN particulate (Ni-P-BN) is also shown.

Figure 23 is a cross-sectional microstructure of the plated layer. Figure 24 shows the magnified view of the Ni dispersing SiC particles. Polygonal SiC particles of about 2 m can be seen. This plating was originally developed to coat the unique combustion chamber of a rotary engine in the 1960s. This plating forms a composite Ni layer containing particles or fibers. The SiC particle addition of around 4% is widely used. Cubic boron nitride (CBN) is also used, since its friction coefficient is lower than that of a small addition of phosphorus in the electrolyte22 enriches P in the Ni layer, giving age hardening. Age hardening is an increase in hardness over time after exposure to elevated temperature, caused by small and uniformly dispersed precipitates. Figure 2.30 compares hardness changes of some plated layers by heating (ageing); including Ni-SiC compositeplating and hard chrome plating. The Ni-SiC plating without P (Ni-SiC) and the hard chrome plating continually soften with increasing temperature, while the Ni-SiC with P (Ni-P-SiC) increases in hardness up to 350C. The resistance to scuffing of the plated chromium layer is lower than that of the Ni-SiC composite plating with P. The plated chromium contains chromium hydride just after plating. The hydride generates high lattice strainto raise the hardness of the chromium layer. As the hydride decomposes with heating, the chromium layer softens. This is why the hard chromium plating is not so resistive to scuffing. On the other hand, the Ni-SiC plating with P hardens with heat, which improves resistance to scuffing.

Thermal spray

The hyper-eutectic Al-Si block

Cast-in composite

A pre-form consisting of sapphire and carbon fibers is first set in the die. Then, medium-pressure die casting encloses the pre-form in the aluminum block. This process modifies the bore becomes a metal matrix composite (MMC). The wear resistance is nearly the same as that of a cast iron liner. The piston should be plated by iron to prevent seizure. The average thickness of the block is greater and the production cycle time is longer compared to the standard high-pressure die casting block.

Casting technologies for aluminium cylinder blocks

The two-stroke cycle engine cylinder

Two-stroke petrol engines for motorcycles use a loop-scavenging method called the Schnuerrle system. Figure below shows a cutaway view of an aircooled cylinder block. This is an aluminum block enclosing a cast-in liner.

Unlike the simple cylinder shape of a four-stroke engine, the two-stroke cylinder has several portholes for inlet (suction), exhaust and scavenging in the bore surface. The portholes are connected to the gas passages in the block. The combustion gas flows in and out through these portholes.

Additionally, water-cooled engines have complex coolant passages. These shapes are cast as hollow shapes using a sand core.

Several types of cylinder structures have been developed. Low power output engines such as those for a small scooter often use cast iron monolithic blocks, because of their low cost. It is difficult to obtain a uniform pearlite microstructure along the cylinder bore because rapid solidification generates hard carbide at the thin rib between the portholes.

This is called chill. When this appears, the hard microstructure lowers the dimensional accuracy of the bore after machining, damaging tribological properties. The high vanadium content (High-V cast iron) prevents chill and helps create a homogeneous pearlite microstructure.

The composite cast cylinder is used for models requiring high cooling performance. This two-metal structure encloses a cast iron liner having porthole openings. Figure shows a shell core holding a cast iron liner. This integral core is placed into the holding mold. Molten aluminium is then poured into the mold. After shaking off the sand, a porthole opening connected to the gas passage like that in Fig is obtained.

High-performance models of two-stroke engines use surface modification methods like Ni-SiC composite plating. The area around the exhaust port is likely to overheat when the bore wall temperature is high, causing distortion of the bore wall. A plated aluminium block is successfully used to avoid this unfavourable distortion and for better cooling performance. Two-stroke outboard marine engines have comparatively simple porthole shapes. The cast iron liner is shrunk in to the aluminium block.

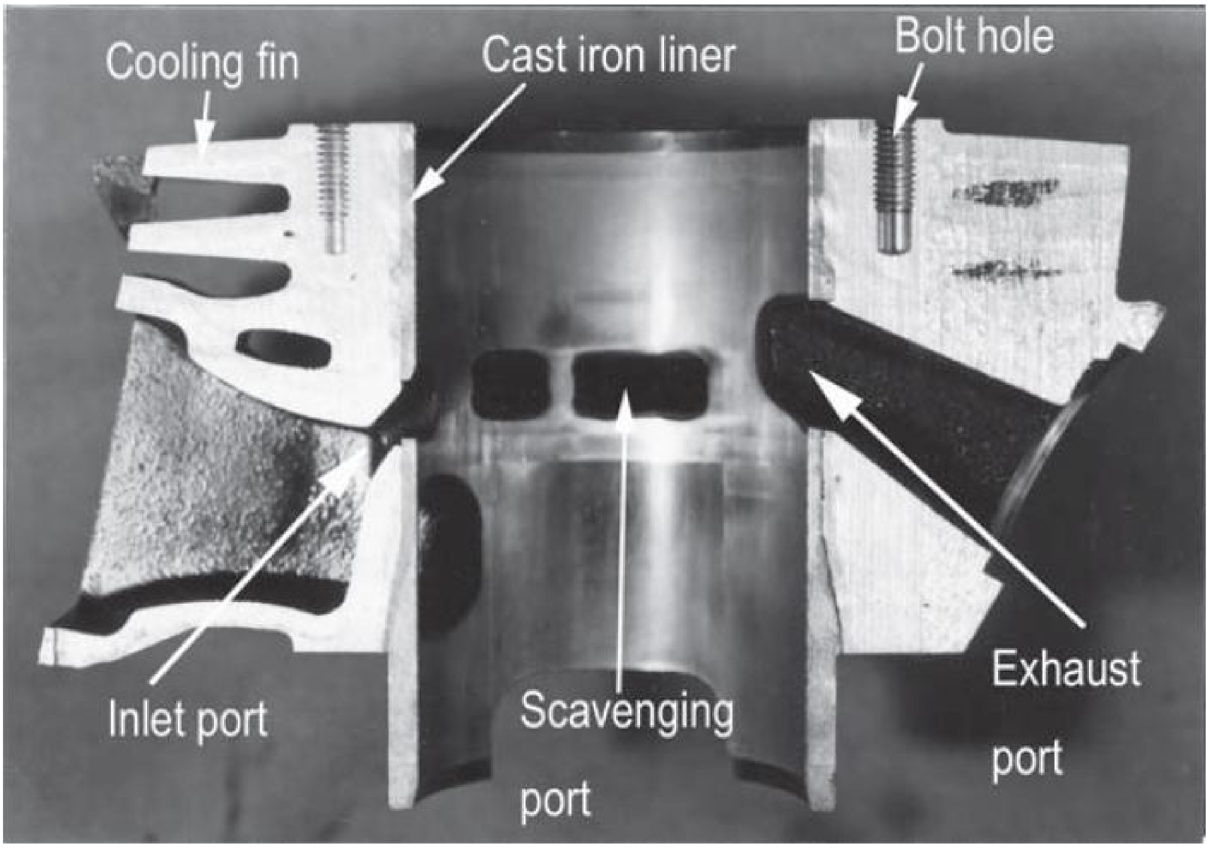

Figure : Crosscut view of an air-cooled two-stroke cylinder enclosing a cast iron liner.