MATERIALS OF THE CYLINDERBLOCKS

Subject: Materials Science

MSc presentation
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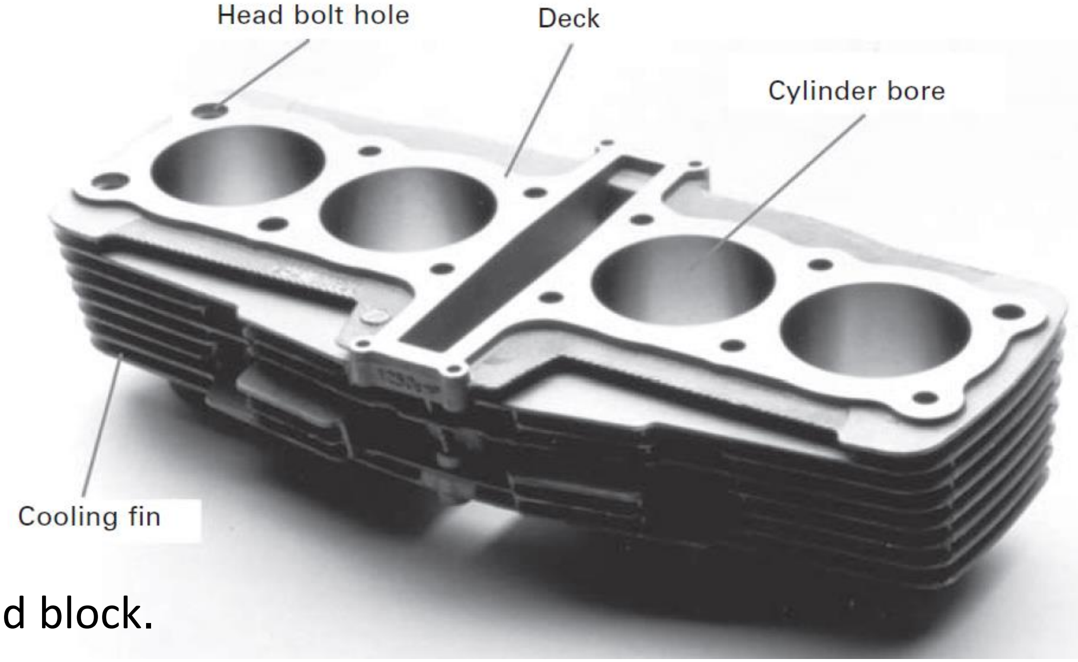
FUNCTION

The cylinder block is the basic framework of a car engine. It **supports and holds all the other engine components**.

The **piston rapidly travels back and forth** in the cylinder under combustion pressure. The **cylinder wall guides the moving** piston, **receives the combustion pressure**, and **conveys combustion heat outside** the engine.

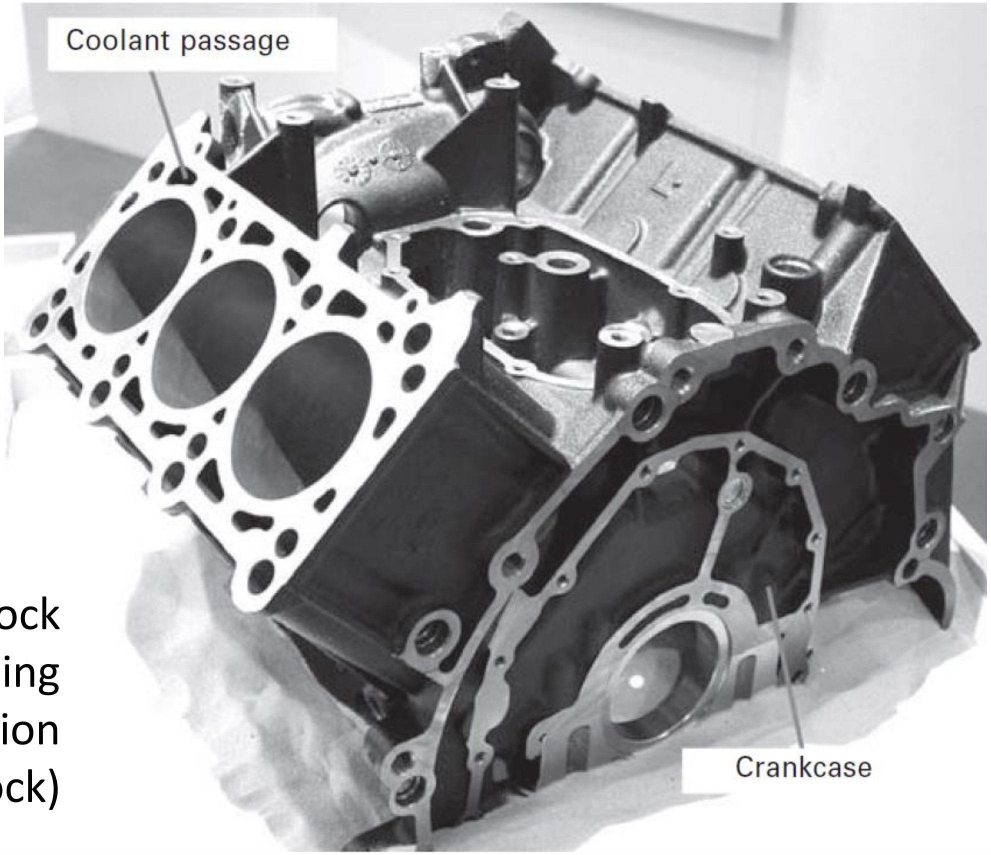
The figure shows a typical cylinder block **without an integrated crankcase**.



Air-cooled block.

FUNCTION

The figure shows the **block with the upper part of the crankcase included**.



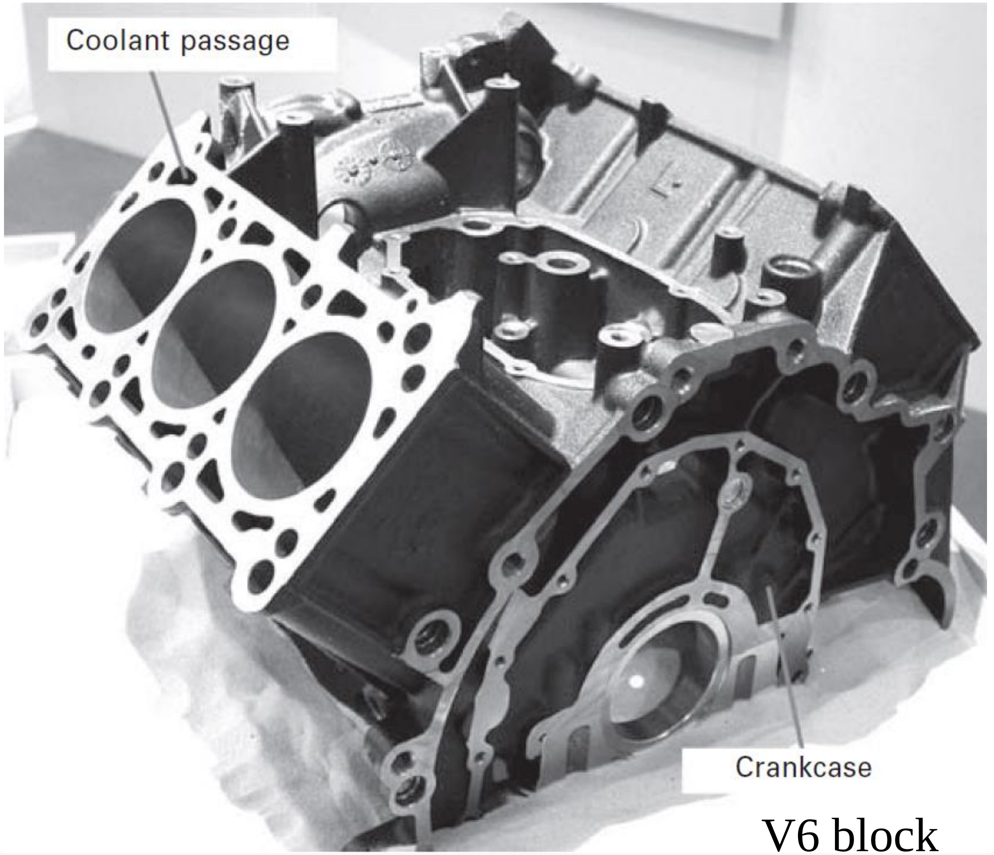
Cast iron cylinder block
(closed deck type) including
a crankcase portion
(water cooled block)

FUNCTION

An engine generating high power output requires more cooling, since it generates more heat. Automotive engines have **two types of cooling systems**, **air-cooled and water-cooled**.

Slide 2 shows the air-cooled type and this slide the water-cooled type.

Whilst an **air-cooled engine may use a much simpler structure** because it does not use the water-cooled system, **the heat management of the cylinder block is not as easy**. As a result, **most automotive engines nowadays use water-cooled systems.** It would be no exaggeration to say that the required cooling level for an individual engine determines its cylinder structure.

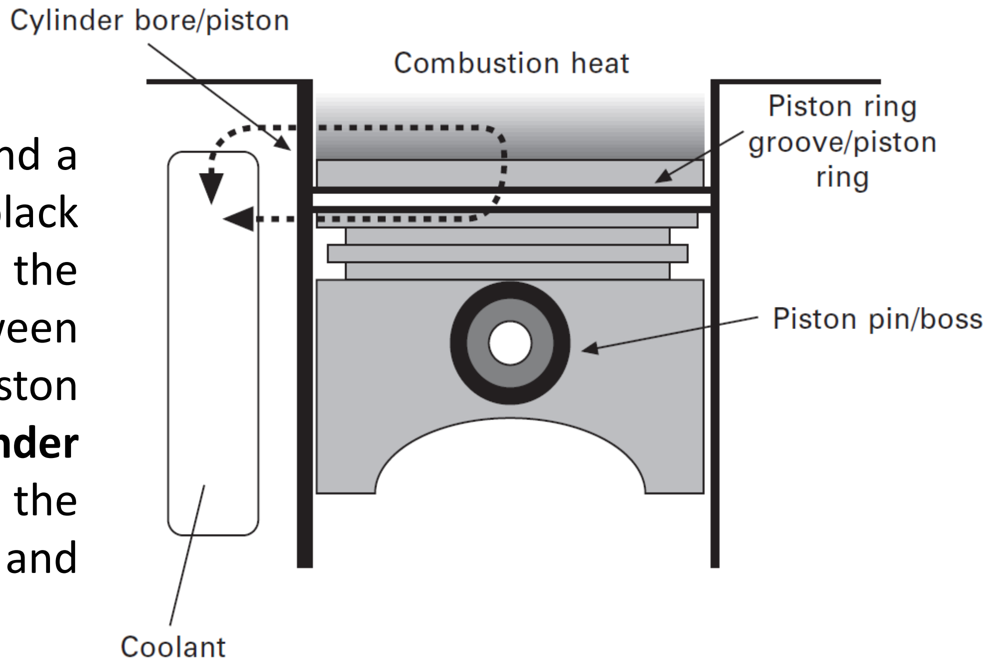


V6 block

FUNCTION

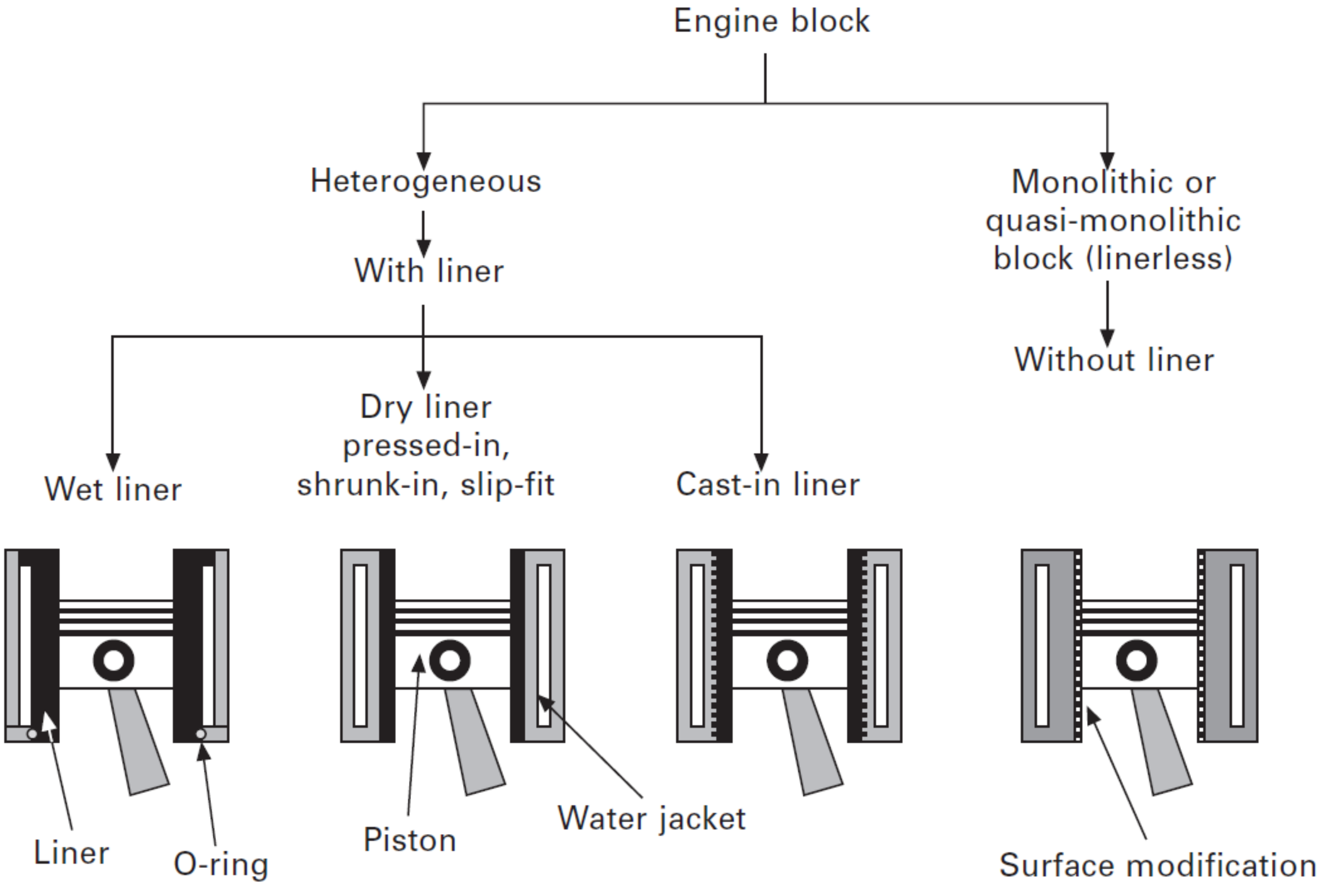
The figure schematically illustrates the **relative positions of the cylinder, piston and piston ring**. The **black portions** indicate the **areas that are most exposed to friction**. These **parts need to be carefully designed** not only from the viewpoint of lubrication but also tribology, as this has a significant influence on engine performance.

Tribological system around a cylinder bore (black portions). These are: the running surfaces between the piston pin and piston boss, **between the cylinder bore and piston**, and the piston ring groove and piston ring.



FUNCTION

There are **four different types** of cylinder block structure.

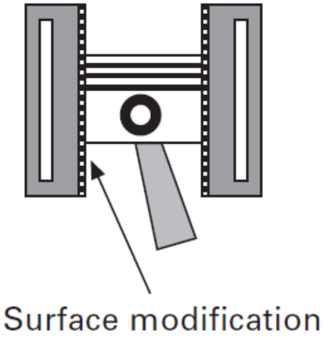


FUNCTION

The **monolithic** or quasi-monolithic block (on the right) **is made of only one material**. It is also called a **linerless block** because it does not contain liners.

The **bore wall** consists of **either the same material** as the block **or a modified surface** such as plating **to improve wear resistance**.

It is normally difficult for one material to fulfill the various requirements. However a liner-less design in multi-bore engines can make the engine more compact by decreasing inter-bore spacing.

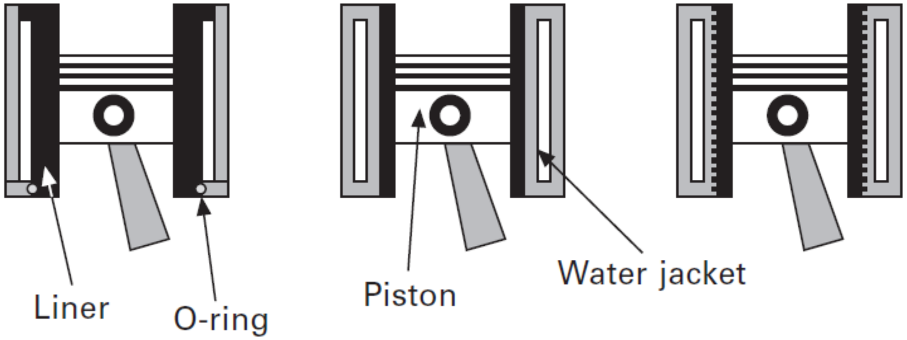


FUNCTION

A **liner** is also called a **sleeve**.

A **wet liner is directly exposed to coolant at the outer surface**. It must be made **thicker than a dry liner**.

A **dry liner** presses or shrinks into a cylinder that has already been bored. Compared to the wet liner, this liner is **relatively thin** and **is not exposed to the coolant**.

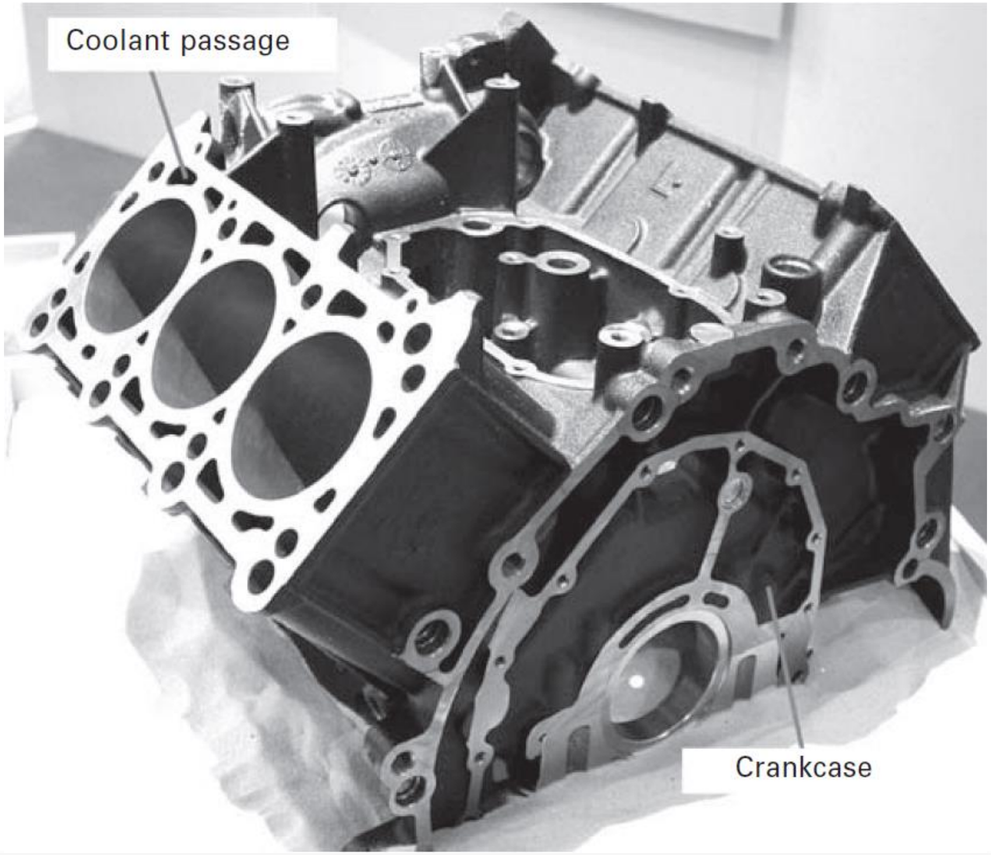


CAST IRON MONOLITHIC BLOCK

The use of cast iron blocks has been **widespread due to low cost** as well as **formability**.

The block is normally the integral type where the **cylinders and upper crankcase are all one part**.

The **cylinders are machined into the block**.



CAST IRON MONOLITHIC BLOCK

The iron for the block is usually **gray cast iron** having a **pearlite microstructure**. The microstructure is shown in the figure. Gray cast iron is so called 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.

CAST IRON MONOLITHIC BLOCK

Cast iron blocks are produced by **sand casting**. For cast iron, the **die casting** process using a steel die is **fairly rare**. The lifetime of the steel die is not adequate for repeated heat cycles caused by melting iron.

As its name suggests, **sand casting uses a mold that consists of 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.

Generally, an **automated molding machine installs the patterns and prepares many molds in the same shape**.
(**3D printing** is often applied.)

CAST IRON MONOLITHIC BLOCK

Two main methods are used for bonding sand. A **green sand mold consists of mixtures of sand, clay and moisture**. A **dry sand mold consists of sand and synthetic binders** cured thermally or chemically.

Molten metal is poured immediately into the mold, giving this process **very high productivity**.

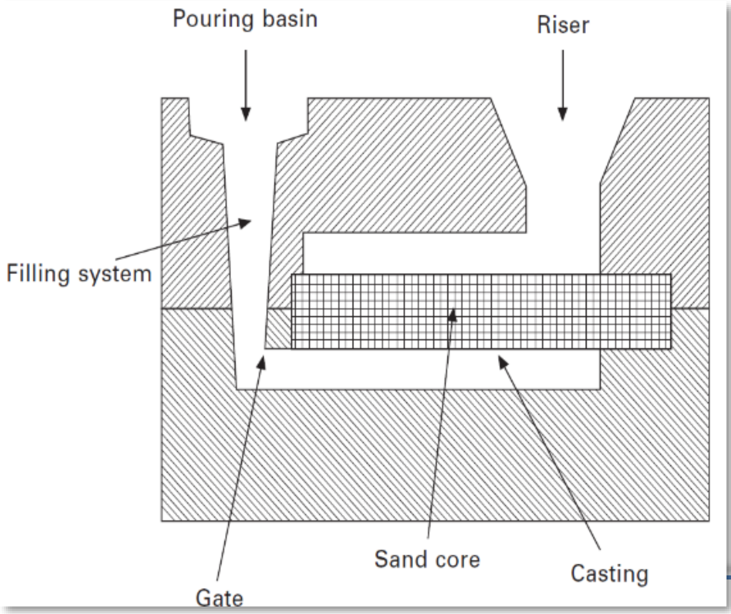
After solidification, the **mold is destroyed** and the **inner sand is shaken out of the block**.

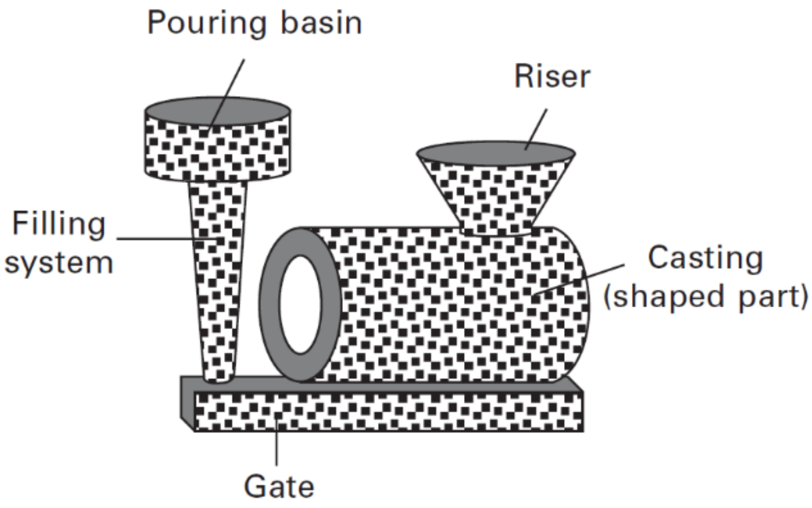
The **sand is then reusable**.


shutterstock

CAST IRON MONOLITHIC BLOCK

Figure 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 is shown in the right side. Normally, 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 are shaped as cored holes.





CAST IRON MONOLITHIC BLOCK

The **graphite** in the cast iron block **works as a solid lubricant** during machining as well as in engine operation. A solid lubricant gives **a low frictional force without hydrodynamic lubrication**. **Graphite, MoS_2, WS_2, Sn, and Pb are all well known as solid lubricants.**

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 discontinuou**s. The resultant **high machinability** gives **high dimensional accuracy to cast iron parts**.

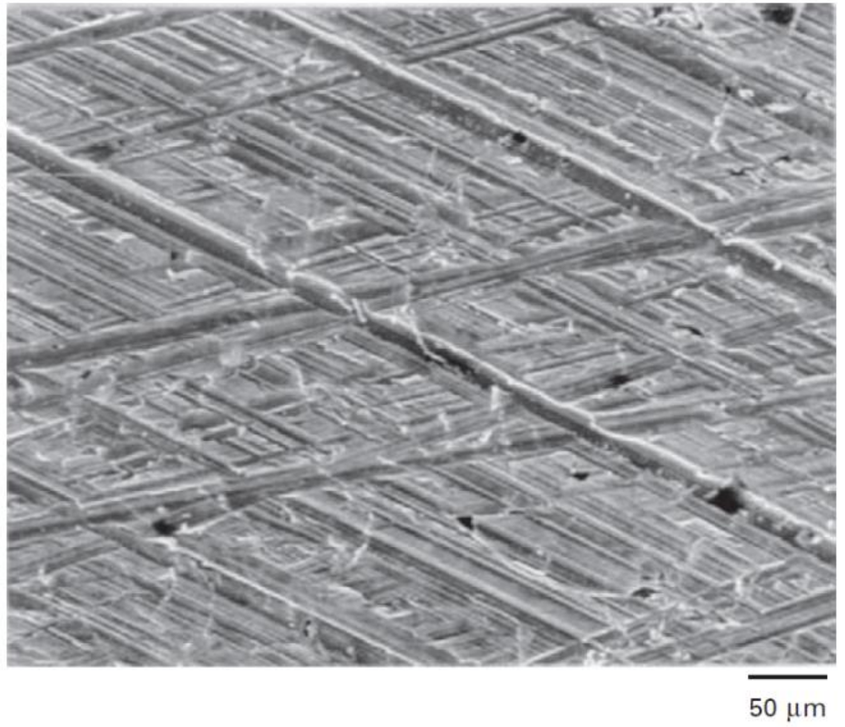
The graphite also works as a solid lubricant to prevent seizure of the piston or piston ring even under less oily conditions.

CAST IRON MONOLITHIC BLOCK

Honing, lubrication and oil consumption

The **cylinder bore** must have high dimensional accuracy. **Honing is the finishing process** used to give accurate roundness and straightness. It is performed **after the fine boring process**. The figure shows a **micrograph of a honed bore surface**.

The honing whetstone carved the **crosshatch pattern**. During engine operation, the **groove of the crosshatch holds lubricating oil**.



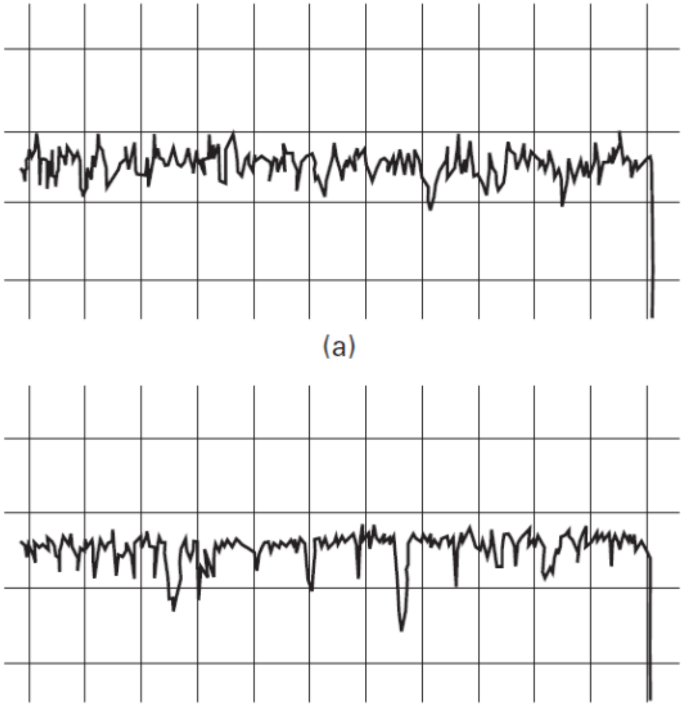
CAST IRON MONOLITHIC BLOCK

Honing, lubrication and oil consumption

The **surface profile determines oil retention** which, in turn, **greatly influences wear resistance**.
An appropriate profile should be established.

One pass finish with the whetstone usually shapes the **surface profile to the normal type** shown in figure (a).

An **additional finish**, scraping off the peak, generates the trapezoid pattern shown in figure (b).
This finishing is called **plateau honing**.


(a)

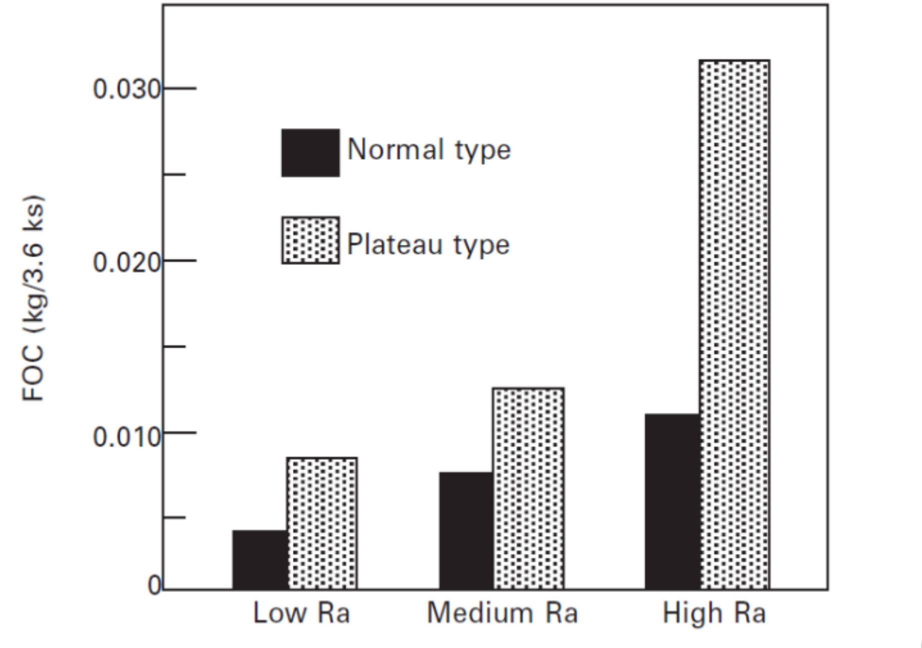
(b)

One graduation of the vertical axis measures 1 μm, that of the horizontal axis 0.1 mm

CAST IRON MONOLITHIC BLOCK

Honing, lubrication and oil consumption

A customer does not want to change engine oil frequently. Less oil consumption is therefore required. The figure compares the oil consumption of a 1.9L car engine, measured by the final oil consumption value (FOC).



For a normal type profile, the low Ra = 0.12 µm, middle Ra = 0.4 µm and high Ra = 0.62 µm.
For the plateau type, the low Ra = 0.14 µm, middle Ra = 0.32 µm and high Ra = 0.88 µm. (Ra means roughness.)

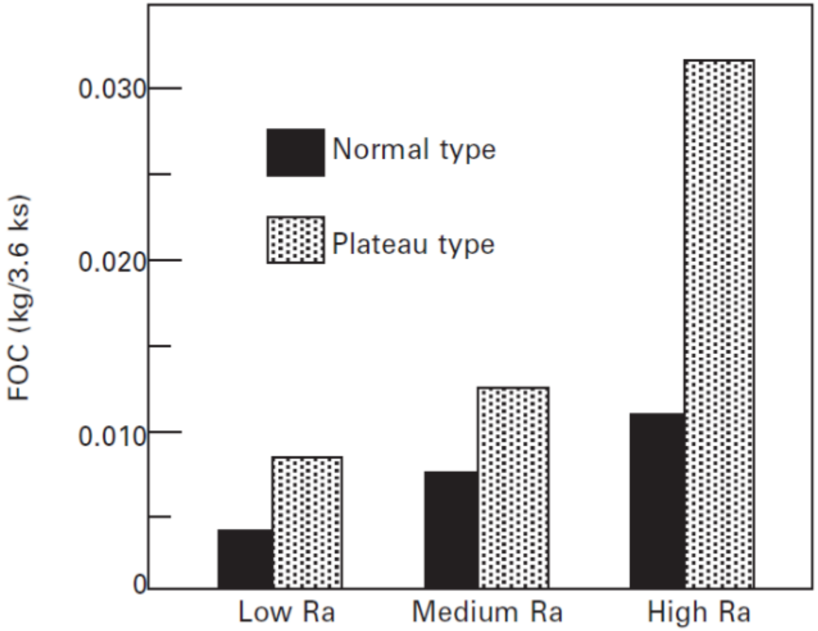
CAST IRON MONOLITHIC BLOCK

Honing, lubrication and oil consumption

The **oil consumption is least in the normal type** of low Ra. However, it is worth mentioning that the **scuffing resistance of the low Ra surface is poor**.
(Ra means surface roughness.)

When the bore wall temperature is high, the plateau surface shows excellent resistance to scuffing although oil consumption is high.

This feature comes from the fact that the plateau shape can maintain more lubricating oil without disrupting the oil film.

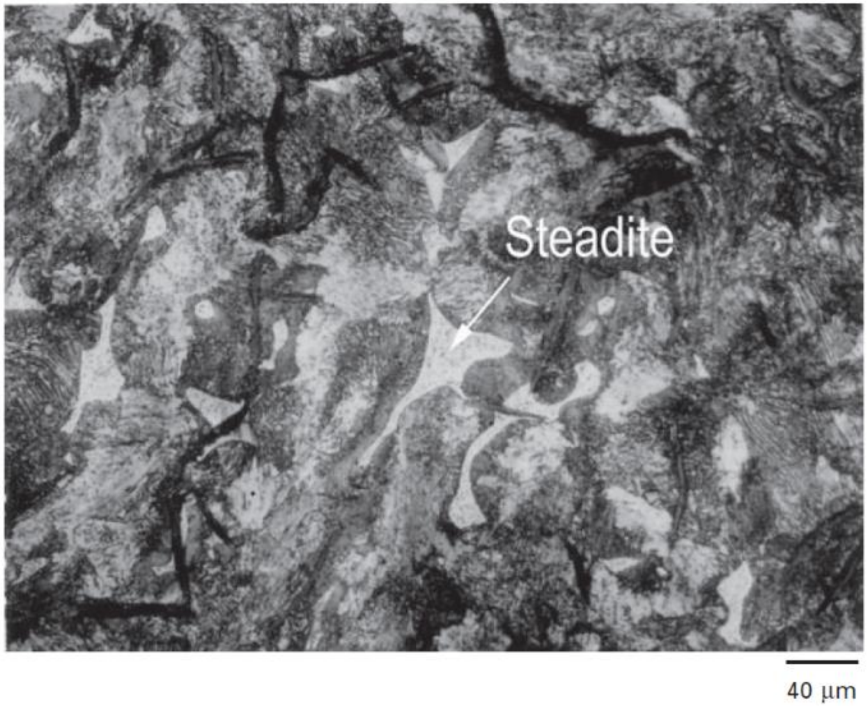


CAST IRON MONOLITHIC BLOCK

Improvement of wear resistance of cast iron blocks

The bore wall should have high wear resistance. To raise durability, a **hard gray cast iron containing phosphorus (P) is often used**. The figure shows the microstructure of high-P cast iron. The **matrix has a pearlite microstructure**, **Steadite is a eutectic crystal containing Fe_3P compound and ferrite. It appears typically in the cast iron of 0.3% P and over**.

The curious shape of 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**.



CAST IRON MONOLITHIC BLOCK

Improvement of wear resistance of cast iron blocks

The mileage required for commercial diesel engines is very high, being as much as 1,000,000 km. These engines have high combustion temperatures.

Engines requiring very long durability use additional heat treatment on the bore surface. A **nitrided liner is often enclosed to increase hardness**. A **phosphate conversion coating on the liner also prevents corrosion**.

Instead of enclosing a hard liner, interrupted **quench hardening by laser or induction heating can also be applied** to the bore wall of the monolithic cast iron block.

CAST IRON MONOLITHIC BLOCK

Improvement of strength

There have been trials to improve the strength of gray cast iron without losing its superior properties. Petrol engines have cylinder pressures ranging from 7 to 12 MPa, while heavy-duty diesels operate in excess of 20 MPa.

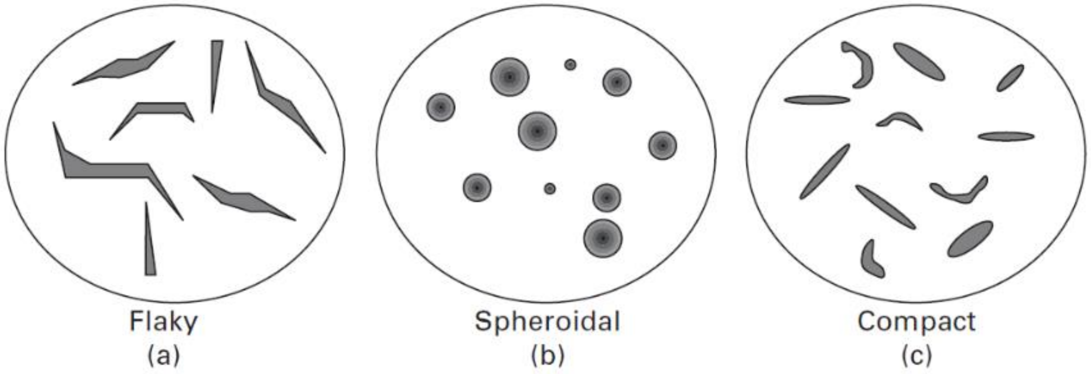
This **high pressure generates much higher mechanical and thermal stresses** on the cylinder block.

The use of a cast iron block is widespread because of the high strength needed. However, a **much stronger material is required to enable a lightweight design with decreased thickness**. For these requirements, a block made of **compact graphite iron has been proposed**.

CAST IRON MONOLITHIC BLOCK

Improvement of strength

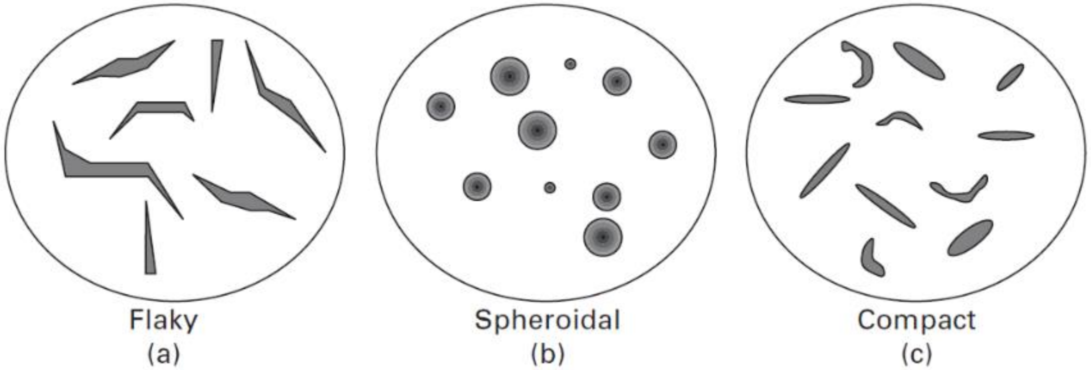
The graphite shape greatly influences the material characteristics of cast iron. The figure gives a schematic representation of graphite morphology. In the **conventional casting procedure**, cast iron generates a **flaky shape** (a) in the iron matrix. However, when a special **modification treatment** is implemented on the molten iron just before pouring, **graphite becomes round** (b). Cast iron having this shape is called **spheroidal graphite cast iron** or nodular cast iron. The additive for spheroidizing is called a nodularizer.



CAST IRON MONOLITHIC BLOCK

Improvement of strength

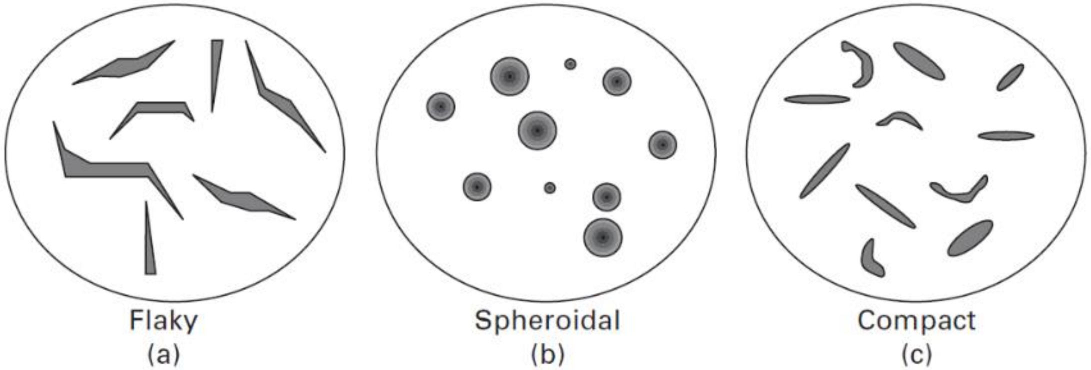
Compared to the flaky shape, **spheroidal geometrical shape can avoid microstructural stress concentration** to give **higher mechanical strength and ductility**. This is also referred to as ductile iron. However, the **thermal conductivity, resistance to scuffing and vibration damping are not so high**.



CAST IRON MONOLITHIC BLOCK

Improvement of strength

The third microstructure (c) is compact graphite iron (CGI) containing graphite of a vermicular (worm-like) form (c). This is a **relatively new alloy** that has **improved mechanical strength without diminishing the favourable properties of flaky graphite iron**. As may be inferred from the shape, the properties of this iron are positioned between flaky and spheroidal iron. It has a **higher tensile strength being 1.5 to 2 times as strong as flaky iron**, **higher stiffness and approximately double the fatigue strength of flaky iron**. The thermal conductivity lies between flaky and spheroidal iron. This makes it possible to produce a cylinder block that is both thinner and stronger.



CAST IRON MONOLITHIC BLOCK

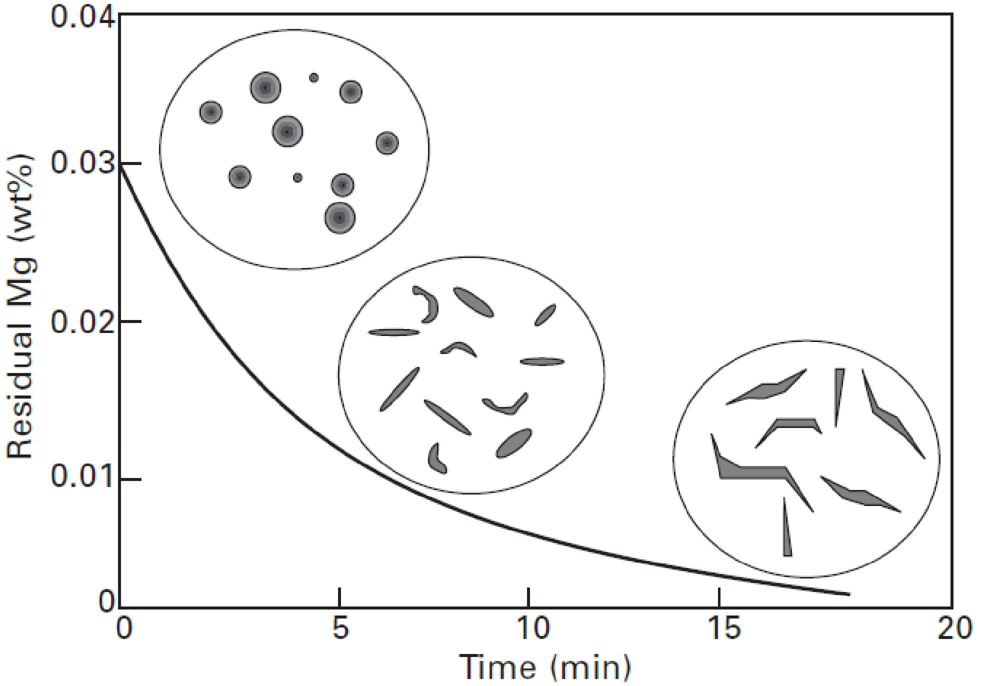
Improvement of strength

The nodularizer inoculated in the molten iron gives perfect spheroidal graphite. An **imperfect spheroidizing treatment before pouring generates CGI**. The **nodularizer contains Mg**.

After the inoculation of the nodularizer, the graphite shape gradually changes to a flaky shape via a vermicular shape as shown in the figure.

The residual Mg content in the molten iron decreases with time due to the **evaporative nature of Mg**.

This causes degradation of the spheroidal graphite to give CGI.

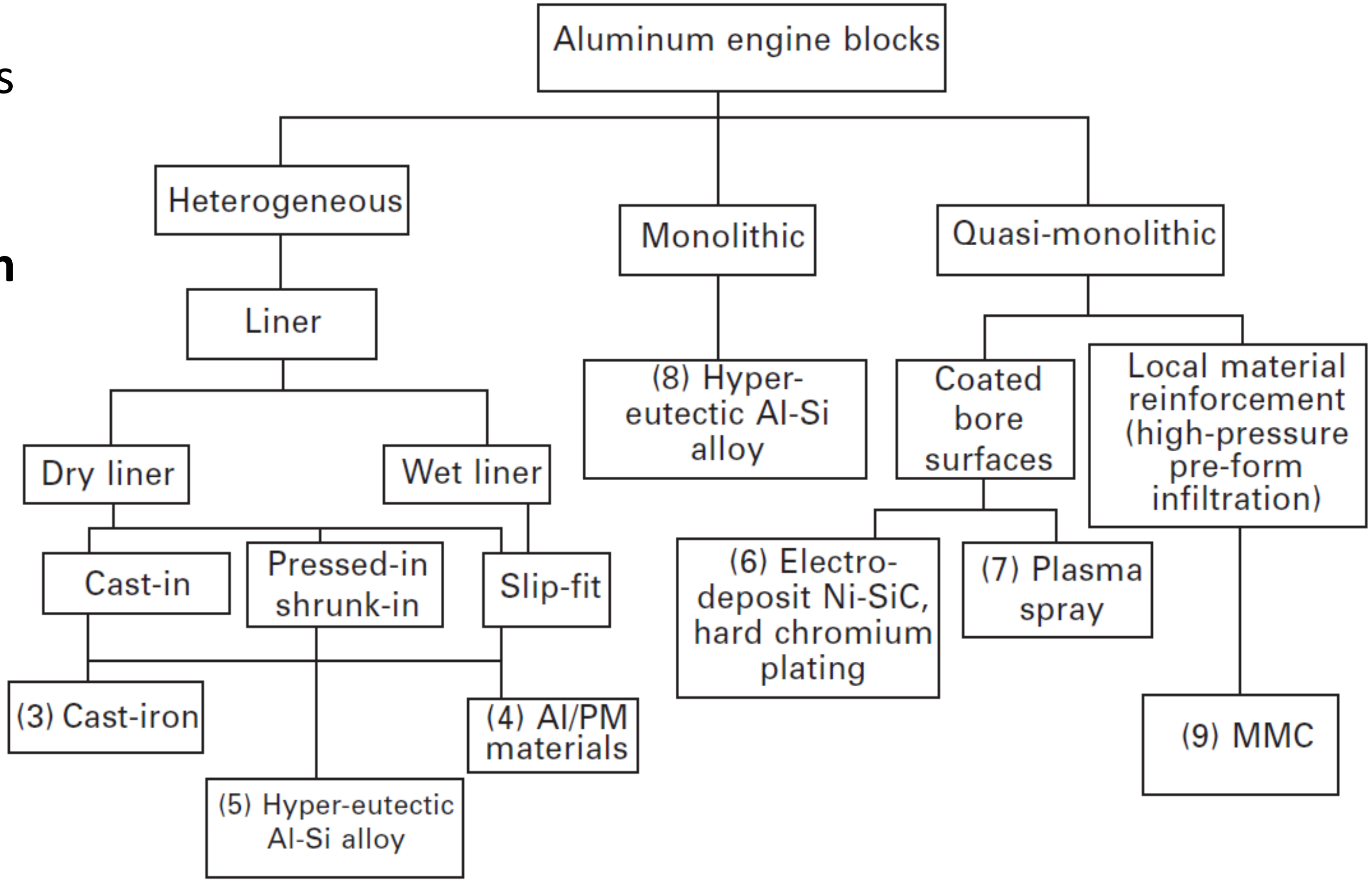


ALUMINUM BLOCKS WITH ENCLOSED CAST IRON LINERS (to improve cooling performance)

Before the millennium, with the exception of sports cars, **car engines mainly used cast iron monolithic blocks**. This was due to the fact that **most cars did not require high power** output and **cast iron was inexpensive**.
Aluminum was weaker, than cast iron. It was thought that an aluminum block must be made much thicker than a cast iron block. However, **if it is well designed, an aluminum block can be both much lighter and almost as strong as the cast iron block.** In a recent comparison, **an aluminum block can attain 40% reduction** in weight compared to its cast iron equivalent. Despite the **greater cost of aluminum**, the **demand for better fuel consumption** has resulted in a **significant increase in the production volume of light aluminum blocks**.
Aluminum blocks were used in 60% of European car engines in 2003.

ALUMINUM BLOCKS WITH ENCLOSED CAST IRON LINERS (to improve cooling performance)

The figure summarizes **types of design for aluminum blocks**, including **modification technologies for the bore surface**.



ALUMINUM BLOCKS WITH ENCLOSED CAST IRON LINERS (to improve cooling performance)

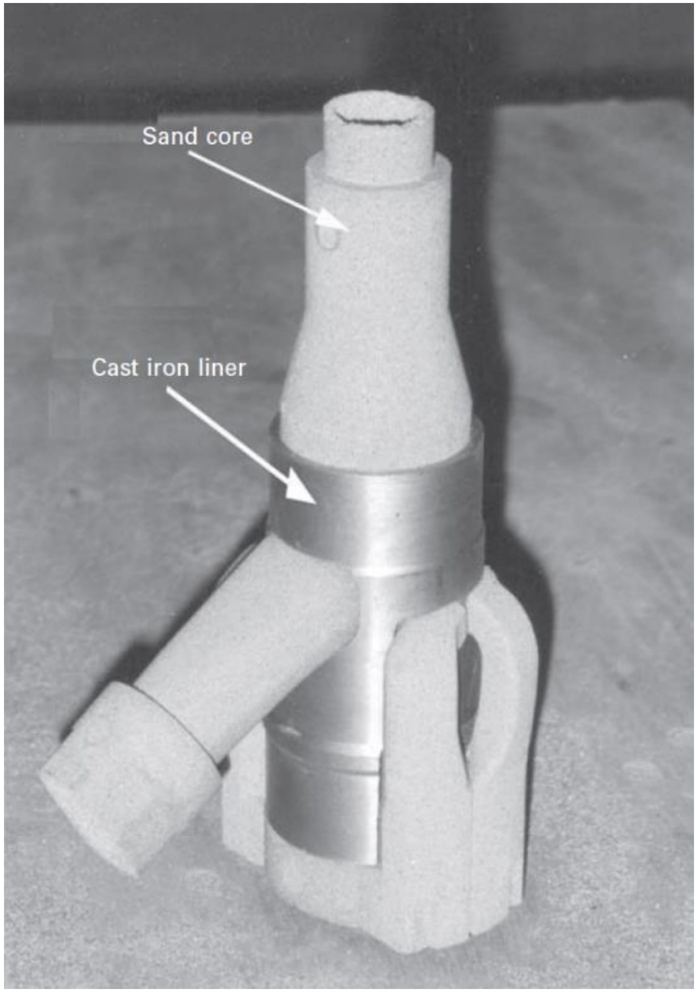
First, we will see blocks enclosing liners, followed by monolithic blocks.

The **aluminum alloy used for blocks has a thermal conductivity of 150 W/(m · K). Cast iron has a thermal conductivity as low as 50 W/(m · K).** The thermal conductivity of aluminum is therefore **three times that of cast iron**. Since the **density is 1/3 that of cast iron**, aluminum alloy can give **high cooling performance at a lower weight**. However, **it is soft** and the **wear resistance is generally low**. To **deal with this problem, aluminum alloy blocks with enclosed iron liners** (normally cast iron) **are widely used**. Historically, this composite structure was particularly developed for aeroplane engines which needed to be of light weight. For example, the Wright brother's engine (1903) powered the first self-propelled, piloted aircraft. It had a water-cooled, petrol, four-stroke, four-cylinder engine. To lower the weight, a cast aluminum engine block containing a crankcase was used. The cylinder portion enclosed screwed steel liners.

ALUMINUM BLOCKS WITH ENCLOSED CAST IRON LINERS

In a block enclosing an iron liner, three types have been developed as shown in Slide 6.
The **cast-in design is the most widespread**.
This is called a **composite cast cylinder block**.
In this manufacturing process, **molten aluminum is poured into the mold in which a cast iron liner is already placed**. The hollow space surrounded by the liner is stuffed with a **sand core**.
The **mold and core are decayed after casting**, so that the **aluminum block enclosing the cast-in liner remains**.

The complex gas (and coolant) circuits are three-dimensionally designed to have a proper flow.
The **core shapes hollow circuits** in the block.



ALUMINUM BLOCKS WITH ENCLOSED CAST IRON LINERS

After casting, a **two-metal structure** is obtained in which **the liner is firmly enclosed**.

This composite block has a **residual shrink force on the liner**. This is caused due to the fact that the **larger thermal expansion coefficient of aluminum grips the cast iron liner during cooling after solidification**.
The thermal expansion coefficient of cast iron (10×10^{-6}/°C) is **1/2 that of aluminum** (20×10^{-6}/°C). **The stress remains as a residual stress after finish machining**.

The **residual stress works well when the engine temperature rises**. Typically, the uppermost outside portion of the liner has a temperature of **250 °C in the aircooling type**, and **200 °C in the water-cooling type**. The **heat expands the aluminum portion more than the inside line**r.

Without the residual stress, the liner would loosen, generating a gap.

ALUMINUM BLOCKS WITH ENCLOSED CAST IRON LINERS

The **optimum microstructure suitable for the liner is the same as that required for the cast iron block** (pearlite matrix containing flaky or compact graphite).

The cast iron **liner is normally produced by sand casting**.

A **centrifugal casting** process using a rotating cylindrical die is **sometimes used** to produce a large bore liner.

Since a liner is a **thin tube**, **spray forming technology can also produce a steel liner**.

ALUMINUM BLOCKS WITH ENCLOSED CAST IRON LINERS

In this composite cast design, the **iron liner does not come directly into contact with the coolant**. The **combustion heat must discharge to the coolant through aluminum**. The **heat should pass through the interface between the liner and aluminum**. However, there can be some **metallurgical discontinuity at the interface** that may cause an **air gap**. The **gap obstructs the heat transfer** from the liner to the aluminum body.

To **reduce any gap**, a **number of techniques have been proposed**. In permanent mold casting or sand casting, **pre-heating the liner before cast-in is effective**.

The casting plan should be designed for the **aluminum melt to flow** along the surface of the liner **without swirl**. In high-pressure die casting, the **pressurized liquid aluminum is injected at high speed**, so that a gap is unlikely to appear.

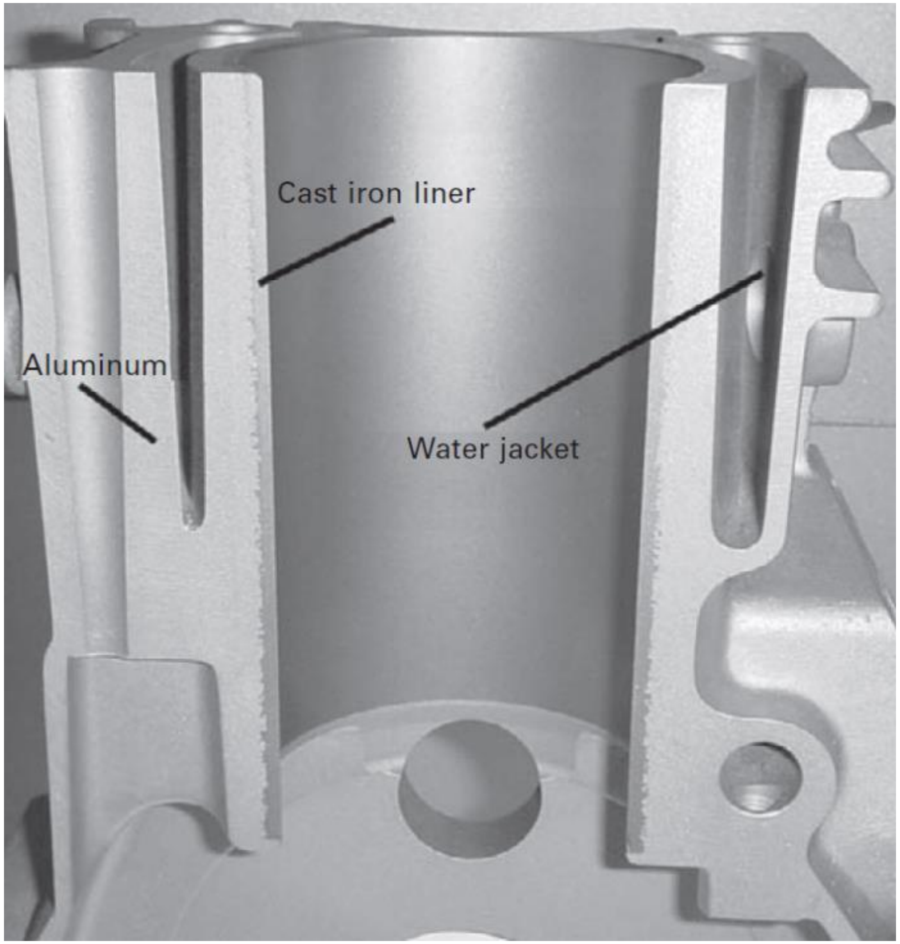
ALUMINUM BLOCKS WITH ENCLOSED CAST IRON LINERS

To generate **strong mechanical interlocking** with aluminum, a cast iron liner having a **dimpled outer surface** has been proposed.

ALUMINUM BLOCKS WITH ENCLOSED CAST IRON LINERS

The figure shows an example where the **aluminum and liner join at the interface without any visible gaps**.

The **dimple gives an excellent heat transfer** property **with its large surface area** and close contact.

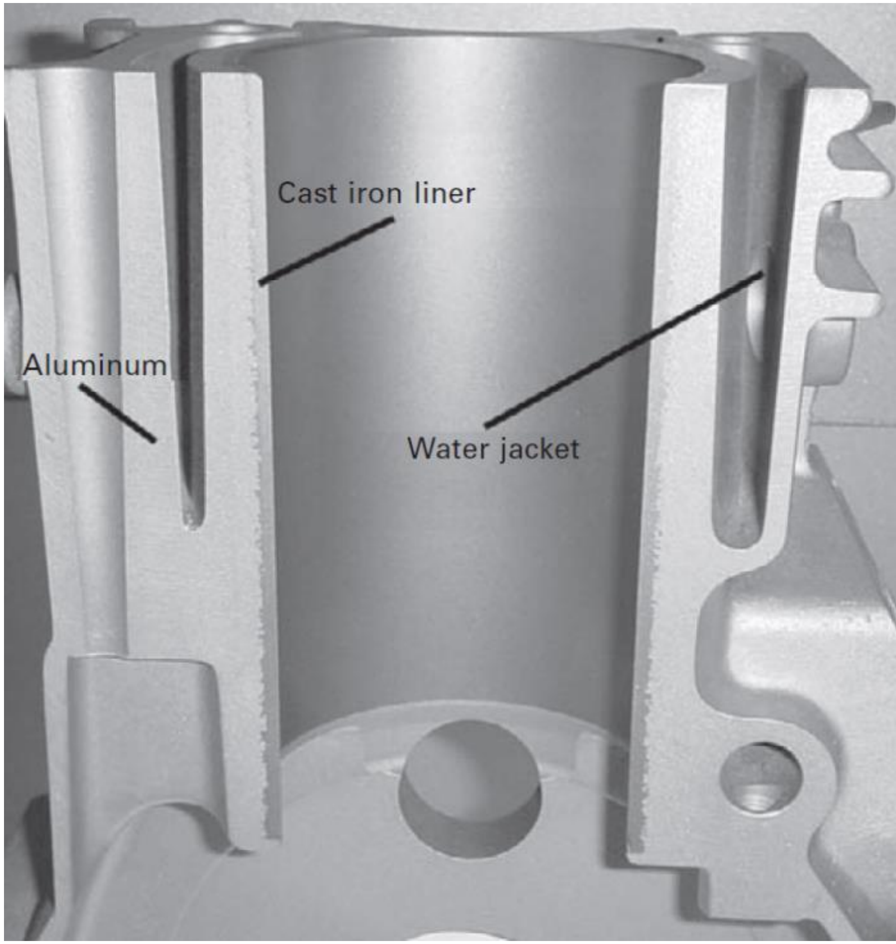


ALUMINUM BLOCKS WITH ENCLOSED CAST IRON LINERS

An alternative method has also been proposed. **An aluminum coating on the outside surface of the cast iron liner** creates good metallurgical continuity with the aluminum block.

The **coated layer works as a binding layer** between the liner and block's aluminum.

Dipping the liner directly into Al-Si alloy melt or **thermal spray** of Al-Si alloy on the liner is used for coating. Even using this method it is, however, necessary to ensure careful casting.



ALUMINUM BLOCKS WITH POWDER METALLURGICAL ALUMINUM LINER (to improve heat transfer)

In a composite cast cylinder, the **heat transfer through a cast iron liner is not that good**. A thick liner reduces heat conduction, raising the bore wall temperature.

A **hard aluminum 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) aluminum alloy.

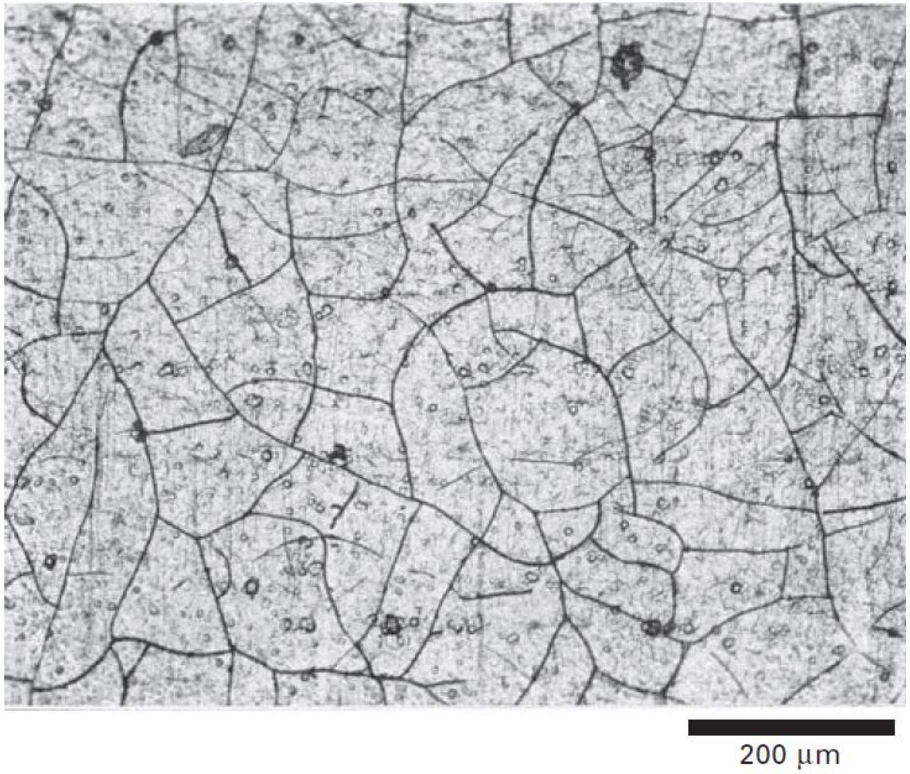
The chemical composition of the liner is Al-17% Si-5 Fe-3.5 Cu-1 Mg-0.5 Mn containing Al_2O_3 and graphite.
The figure shows a typical microstructure.
The **hard Si particles** as well as **finely dispersed intermetallic compounds embedded in the aluminum matrix.**
The liner is cast in by **high-pressure die casting**.

QUASY MONOLITIC ALUMINUM BLOCKS WITH Cr-PLATING

A **thin chromium layer directly plated onto an aluminum-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 the figure.

The **cracks retain oil to generate hydrodynamic lubrication**.

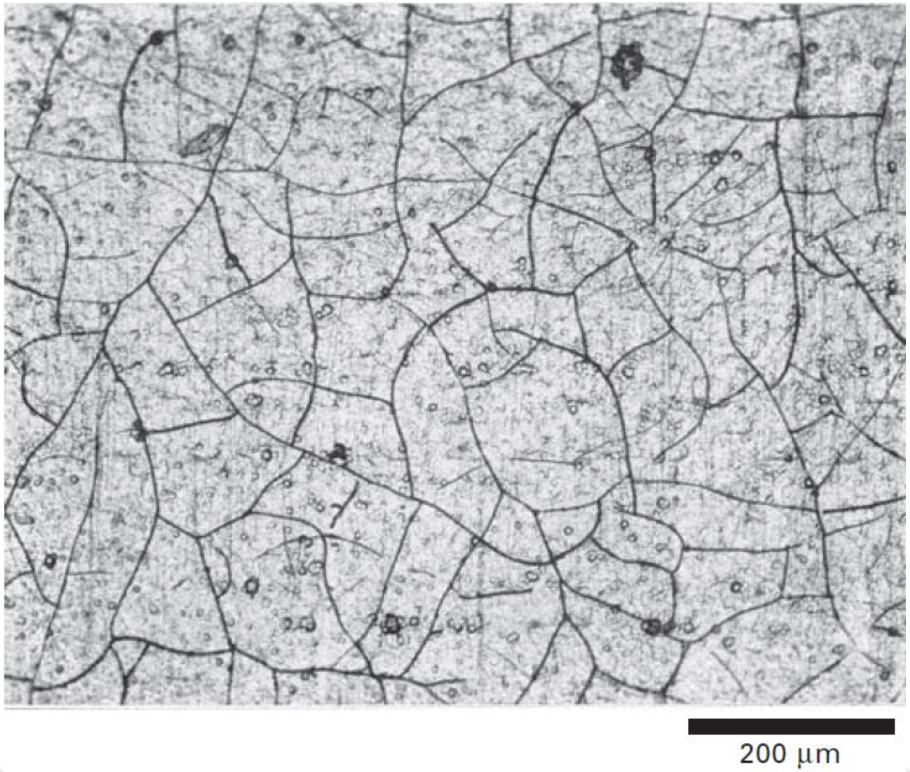


QUASY MONOLITIC ALUMINUM BLOCKS WITH Cr-PLATING

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 (mentioned later).

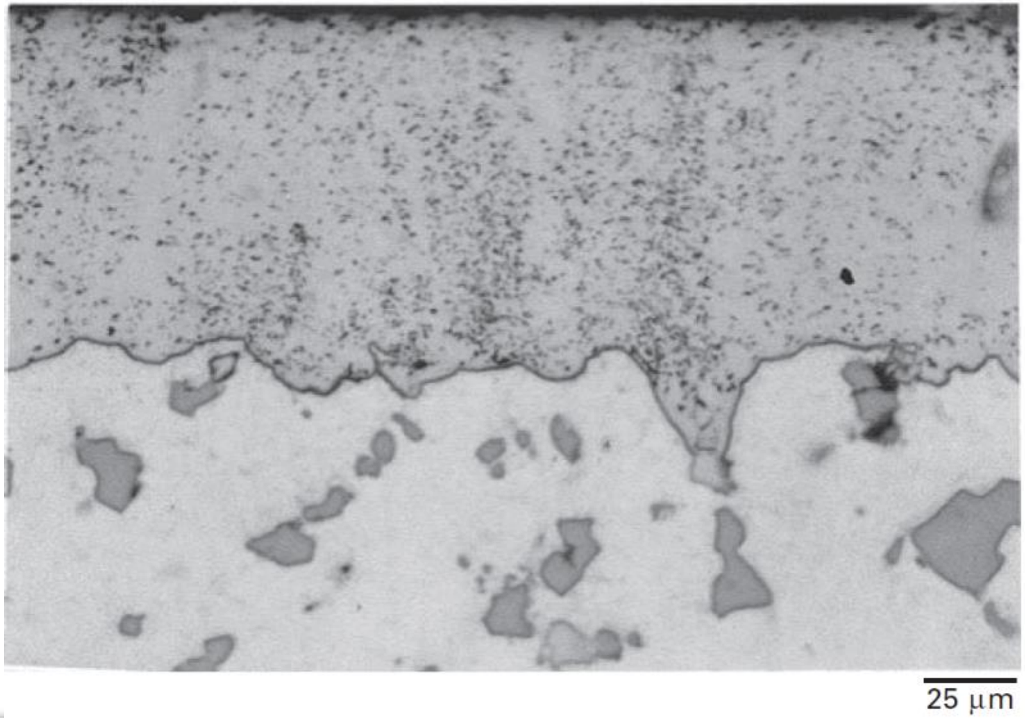
The disposal of waste fluid from the plating facility creates environmental problem.

As an alternative, Ni-SiC composite plating is also used.



QUASY MONOLITIC ALUMINUM BLOCKS WITH Ni-Si-PLATING

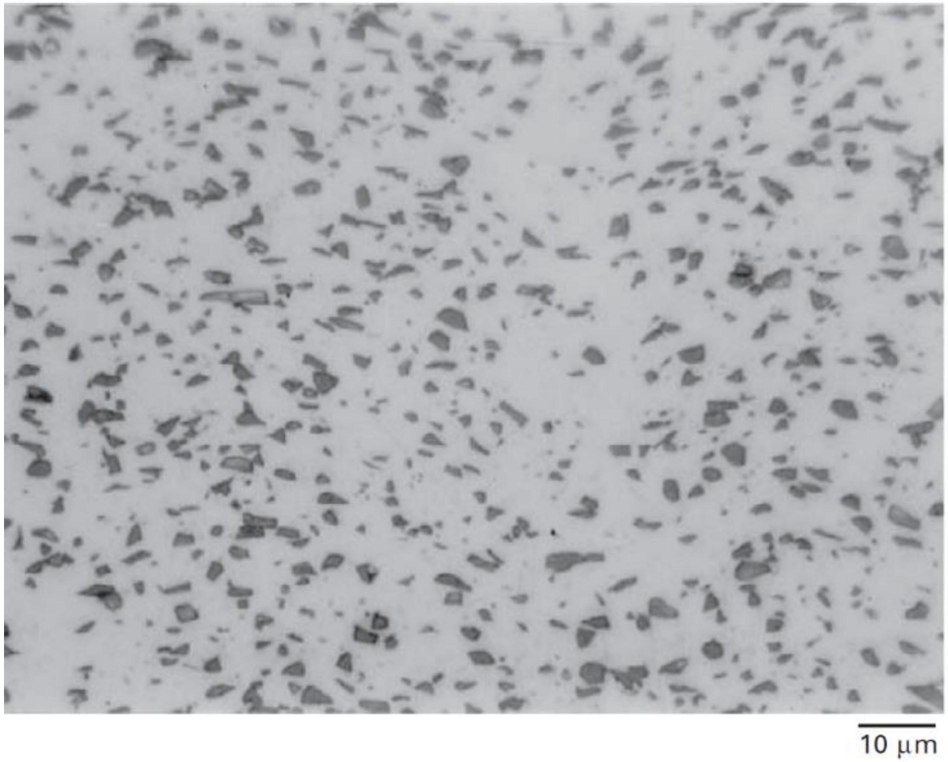
This process generates a **Ni layer dispersing SiC particles**. The piston surface does not require a special coating to prevent scuffing. The figure is a cross-sectional microstructure of the plated layer. The lower portion is aluminum.



QUASY MONOLITIC ALUMINUM BLOCKS WITH Ni-Si-PLATING

The figure shows the magnified view of the Ni dispersing SiC particles. Polygonal SiC particles of about 2 µm can be seen.

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 SiC.



A **small addition of phosphorus** in the electrolyte 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.

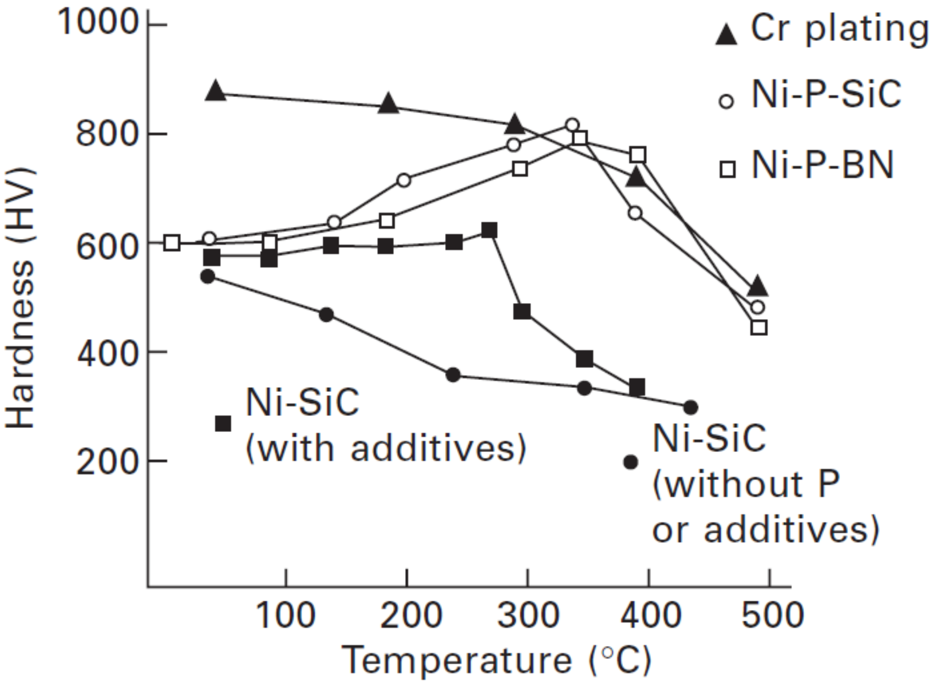
QUASY MONOLITIC ALUMINUM BLOCKS WITH Ni-Si-PLATING

The figure compares hardness changes of some plated layers by heating (ageing); including Ni-SiC composite plating and hard chrome plating.

The P added specimens show higher hardness around 350 °C.

The specimen with BN particulate (Ni-P-BN) is also shown.

Cr plating results higher Hardness (see next slide).



QUASY MONOLITIC ALUMINUM BLOCKS WITH Ni-Si-PLATING

Cr plating results higher hardness (see previous slide).

However:
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 strain to 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**.

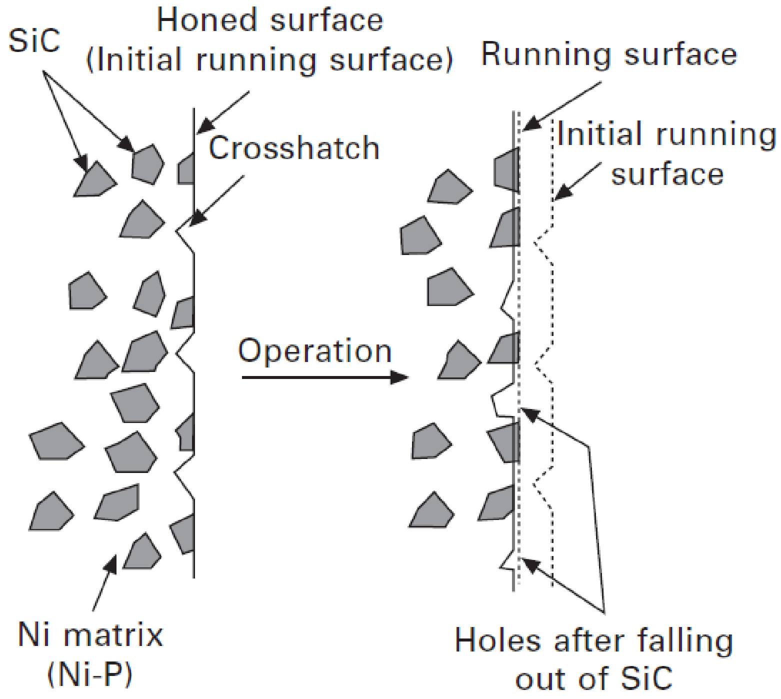
QUASY MONOLITIC ALUMINUM BLOCKS WITH Ni-Si-PLATING

On the other hand, the **Ni-SiC plating with P hardens improves resistance to scuffing**. A diamond whetstone finishes the composite plating **to form an oil pocket. During operation**, even if the **Ni matrix wears, the SiC endures**. The figure schematically illustrates the **changes of surface profile with wear**.

An advanced state of wear is shown on the right.

The **SiC particles need to have a size below 3 µm**. If not, they disrupt the oil film, obstructing hydrodynamic lubrication.

It is also very important to **disperse the SiC particle homogeneously in the Ni layer**. The electrolyte should be carefully stirred to homogeneously suspend the heavy SiC particles.



QUASY MONOLITIC ALUMINUM BLOCKS WITH THERMAL SPRAY

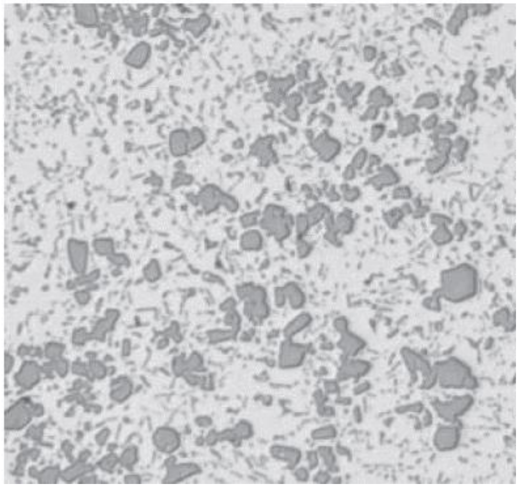
Kawasaki Heavy Industries produced a motorcycle cylinder coated with wire explosion spraying in 1973. Initially this technology was used for two-stroke engines.

The process **thermal-spray**s **high-carbon steel and Mo alternately on the bore of an aluminum block** . The electrically heated wire melts and disperses to deposit on the bore surface. The **Mo layer remains adhesing to the soft aluminum**. Special coating is unnecessary at the piston surface.

A **plasma spray** technique using metal powders has also been developed. It is **very important for the sprayed layer to have close adhesion to aluminum**, since it receives repetitive thermal stress during operation.

MONOLITIC ALUMINUM BLOCKS: hyper-eutectic Al-Si block

This technology makes a **monolithic block with a hyper-eutectic Al-Si alloy**.
The bore surface uses the **aluminum matrix without coating** to produce a **wear resistant surface**. Since this alloy **is not easy to cast**, has generally been used to obtain a sound casting. The Reynolds metal company originally proposed this technology. GM adopted this for their Chevrolet-Vega model in 1971. After that, the technology **spread to Germany**. Yamaha has recently developed the production of blocks by vacuum-assisted **high-pressure die casting**.

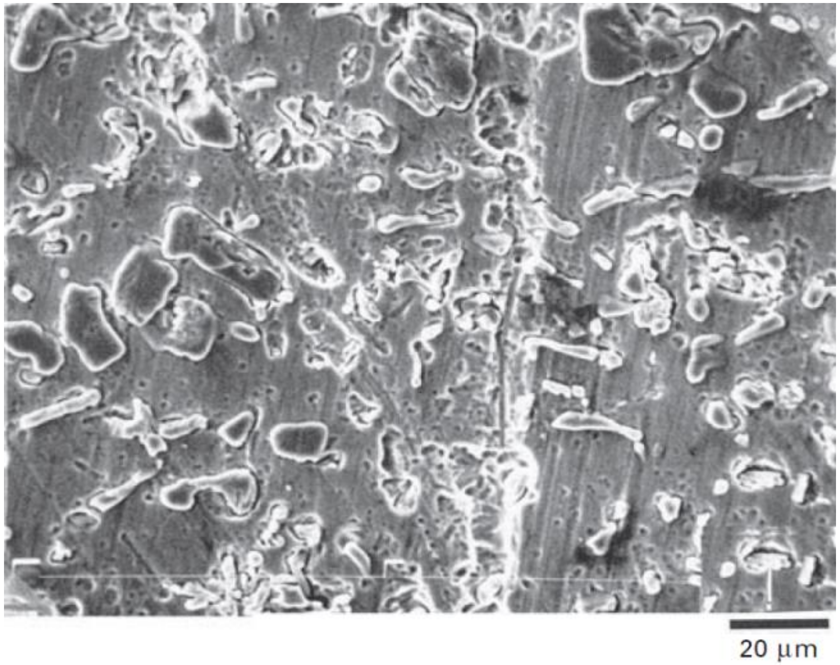


The characteristic microstructure
of the hyper-eutectic Al-Si:
Si grains in the eutectic matrix

MONOLITIC ALUMINUM BLOCKS: hyper-eutectic Al-Si block

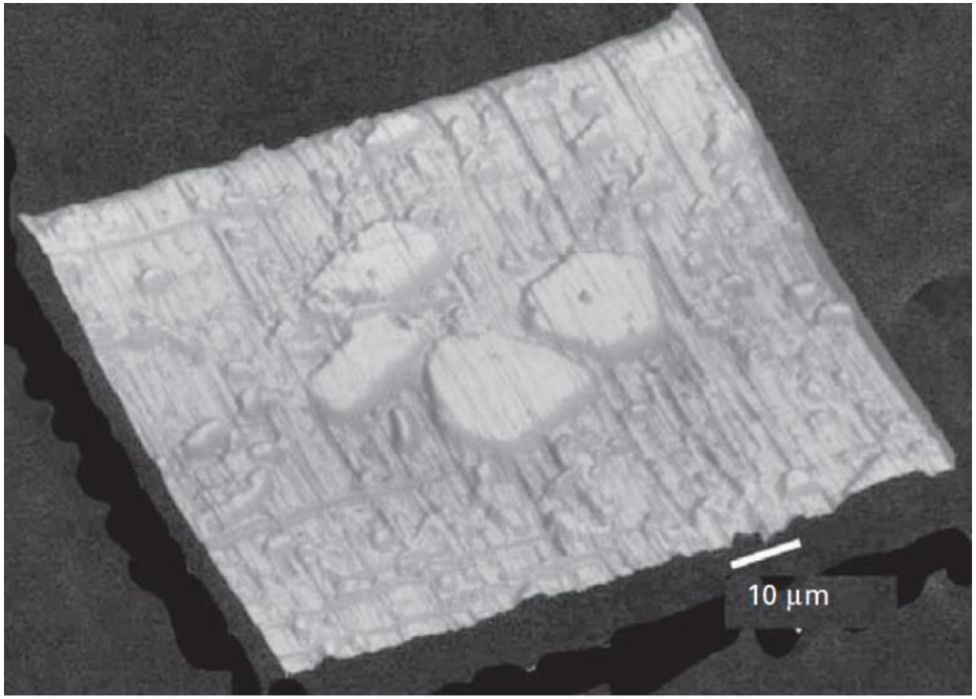
The Si particles work in the same way as the SiC particles in Ni-SiC composite plating. The Si dispersion in the casting must be carefully controlled from a tribological viewpoint. The **hydrodynamic lubrication is greatest at an appropriate height of the exposed Si**. A special finishing to expose the Si is required for the running surface. **To expose Si particles, the bore surface is chemically etched or mechanically finished after fine boring.**

The figure is a scanning electron micrograph of the bore surface, showing primary phase Si particles of about 50 µm.



MONOLITIC ALUMINUM BLOCKS: hyper-eutectic Al-Si block

The figure is an atomic force micrograph, clearly showing **exposed Si particles after finishing**. The slightly depressed **aluminum matrix between the Si particles helps retain oil**.



Since the counter **piston consists of a similar high-Si aluminum alloy**, both running surfaces become a combination of aluminum alloy.
To avoid seizure, the piston surface is covered by plating such as Fe + Sn or Cr + Sn (the Sn layer being on the outside) The machining of the hard alloy is not so easy. However, like a cast iron block, the **fact that the block material forms the bore wall is attractive**. **As a result, production volumes are increasing**.

REFERENCE, SOURCE

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SUGGESTED VIDEOS

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Casting of engineblocks:
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