Applications – Power train – Cylinder linings

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3 Cylinder linings

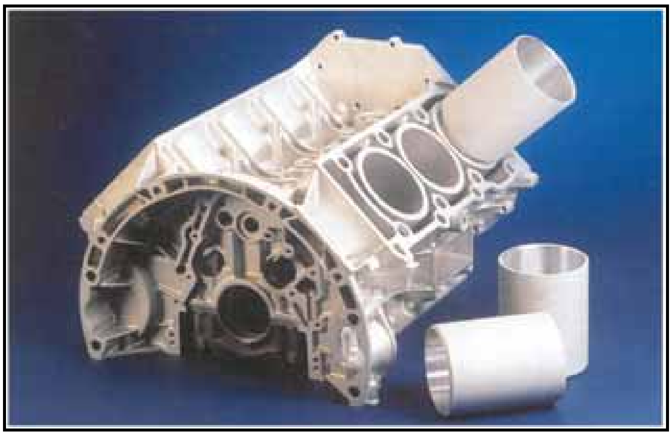
3.1 Introduction

Hypereutectic AlSi liner (SILITEC®)

Source: PEAK

The reduction of friction losses in automotive engines offers big potential when looking for possibilities to cut down fuel consumption. In the engine block, the inner wall of the cylinder bore forms the sliding surface for the piston / piston rings assembly. Thus the specification of the cylinder bore material as well as the topography and the quality of the running surface in the cylinder bore play a crucial role in the optimization process of the tribological system "Cylinder-Piston-Piston ring".

Grey cast iron provides itself a good tribological behaviour for the "Cylinder-Piston-Piston ring" system. However, the ongoing substitution of cast iron in engine blocks by aluminium casting alloys requires the development of a new "tribological system". Aluminium casting alloys - except for the hypereutectic AlSi alloy variants - are not sufficiently wear resistant for this application. Different solutions have been developed over the years ranging from the introduction of cylinder liners consisting of suitable materials as pressed-in or cast-in parts, the application of properly adapted surface treatment or coating technologies to the development of special aluminium alloys. This chapter will cover all applicable concepts, but focus in particular on separate cylinder liners.



V6 aluminium engine block (Daimler) with cast-in SILITEC® liners

Source: PEAK

3.2 Requirements *on the cylinder inner wall / cylinder liners*

Mechanical and thermodynamic losses, wear, and the emissions caused by lubricating oil combustion are principally influenced by the tribological behaviour of the cylinder / piston system. The current trend towards compact engines with high power densities and increased thermomechanical loads increases the importance of this tribological system and requires new approaches in the area of cylinder working surfaces. Consequently, the cylinder inner walls have to withstand higher ignition pressures and higher piston speeds. Furthermore, the precise matching of the cylinder bores with the pistons and piston rings leads to improved engine performance. It has been also shown that a better tribological behaviour can be achieved for properly structured liner surface topographies (i.e. laser-structured liner surfaces) than for conventional plateau-honed surfaces leading to lower fuel consumption and less wear.

Friction and wear

The most important function of the cylinder bore surface is to act as an excellent sliding partner for the piston / piston rings:

- Minimum wear of the cylinder inner walls / cylinder liners
- Minimum wear of the sliding partner (piston ring)
- Minimum consumption of lubricants
- No tendency for galling.

In order to reduce oil consumption and to ensure low friction and good wear resistance, the interaction of the liner and the piston ring (grey cast iron or steel, but today usually coated) must be optimized in a total system approach.

An important aspect is also the operability without lubrication. In general, an oil film supplied from the oil sump ensures sufficient lubrication for the tribological system. However, in case of lack of oil supply, a minimum oil film has to be maintained by the liner to guarantee the engine operation for a certain time period.

Another relevant aspect is the good corrosion resistance of the cylinder bore surface.

The following aspects are relevant if cylinder liners are introduced as separate components (heterogeneous solutions):

Heat extraction

A good thermal conductivity is needed in order to extract the combustion heat and to keep the temperature of the inner surface of the liner sufficiently low. However, heat extraction can only work if a proper thermal contact between the liner and the surrounding engine block material is achieved. The optimum case is a metallic bonding between the liner and the engine block. However, if only mechanical bonding can be realised, at least a small, stable and constant gap must be achieved.

Wall thickness

Regarding the trend towards steadily decreasing inter-bore distances (target < 5mm), the thickness of cast-in or pressed-in cylinder liners becomes increasingly critical. Consequently, solutions where the bulk material is surface treated or coated with a special liner material are getting more important.

Compatibility

Another point to consider is the compatibility of the thermal expansion of the liner and the piston material. It is most important to limit the gap between the piston rings and the liner and hence the blow-by and the oil consumption of the engine to a minimum.

Other targets which have to be considered in the development of cylinder linings are:

- low weight,
- environmental-friendly production,
- good recycling capability and
- low cost.

3.3 Applicable Technologies – Overview

Grey cast iron engine blocks are mainly produced in monolithic form where grey cast iron itself ensures the proper functioning of the tribological system. Another requirement is the creation of optimum surface characteristics that contribute to lower oil consumption and blow-by, produce fewer wear particles and allow shorter running-in times and consequently a long service life.

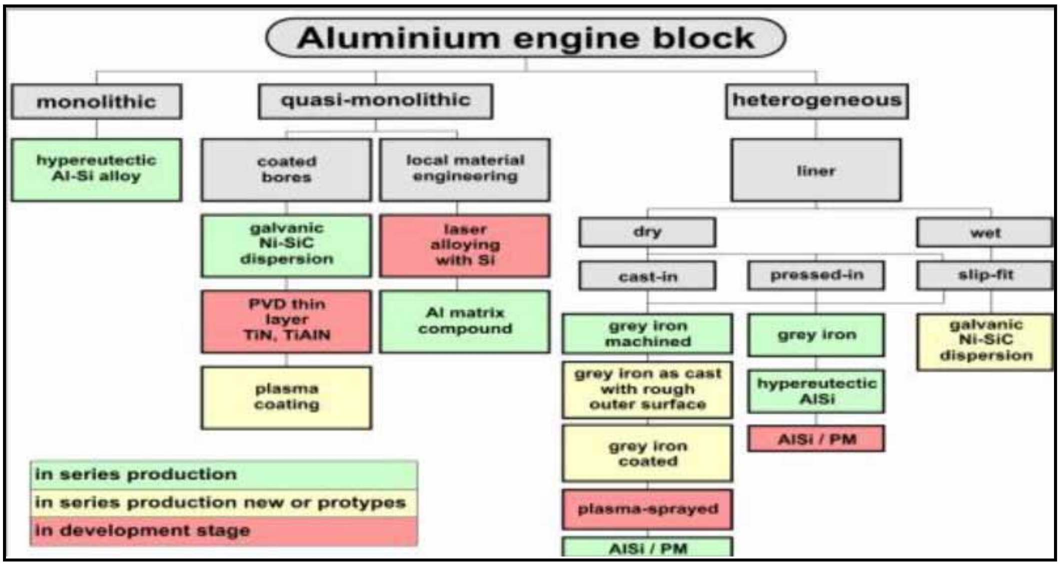
An obvious solution for aluminium engine blocks is to use the well-known grey cast iron as a liner material. The grey cast iron cylinder liners are either cast-in or pressed-in into the aluminium engine block which can be produced from a low cost casting alloy. The drawbacks of this heterogeneous concept are a higher weight (in particular for engines with a high number of cylinders), the lower thermal conductivity and the lack of compatibility and metallic bonding with the surrounding cast aluminium alloy. These problems associated with a heterogeneous material combination are addressed by the use of monolithic or quasi-monolithic concepts based on aluminium.

But cast-in grey cast iron cylinder liners still remain the standard solution, in particular for diesel engines. The application of newly developed cast iron materials, i.e. compacted graphite iron, enables the production of very thin-walled cylinder liners, specifically adapted to the pressure distribution in the engine. Such developments are also important to counter the increasing loads resulting from the use of higher ignition pressures and the higher risk of cavitation.

Transferred to aluminium, the monolithic concept only works with hypereutectic AlSi alloys which, by means of primary silicon particles, provide a comparable wear resistant surface. The disadvantage is that engine blocks made from hypereutectic AlSi alloys are relatively expensive.

Another possibility is to exploit the tribological advantages of the hypereutectic AlSi microstructure in the form of cast-in cylinder liners in an engine block made from another aluminium casting alloy, i.e. an aluminium-based heterogeneous concept. A most convenient aluminium solution would be a quasi-monolithic block with a running surface which is locally created by a suitable coating or surface treatment. New developments like plasma coating and the local surface enrichment with primary silicon are aiming in this direction.

Only monolithic and quasi-monolithic concepts fulfil the request for cylinder units of maximum compactness or, respectively, a cylinder bore as large as possible at a given distance between the cylinders.



Cylinder lining technologies for aluminium engine blocks

Source: Kolbenschmidt

3.3.1 Heterogeneous concept: Grey cast iron liners as cast-in parts

Grey cast iron has excellent tribological properties due to its microstructure consisting of ferrite and lamellar graphite, the latter being a good dry lubricant. Grey cast iron liner can be pressed-in after pre-machining of the engine block. But the lowest cost option is the aluminium engine block with directly cast-in liners. This solution presents two problems:

- **Contact quality:**
  Cast-in grey cast iron liners show no metallic bonding between the liner material and the surrounding cast aluminium alloy, but only a mechanical contact. The quality of the mechanical bond depends on the casting conditions and the surface topography of the cast-in liner, a mechanical clamping with e.g. a suitably machined surfaces is advantageous.

- **Gap formation:**
  The size of the always existing gap between the grey cast iron liner and the surrounding casting alloy may be optimized by a subsequent heat treatment. But the operation of the engine at high temperatures will still lead to a local variation of the heat transfer which is difficult to predict. The smallest gap between the liner and the engine block is achieved in combination with high pressure die casting, but also other casting processes are applicable. Nevertheless substantial development efforts and extensive thermal and stress calculations are necessary in the design phase of the engine block to avoid potential functional problems, in particular in long-term operation.

Conventional cast iron cylinder liner with a machined surface for high pressure die casting application (left) and cross section of a cylinder with cast-in grey cast iron liner (right)

Source: KS ATAG

The use of grey cast iron cylinder liners with rough as-cast outer surfaces is another option to achieve a better mechanical contact when the liner is cast-in. No metallic bonding is achieved, but an improved mechanical contact due to the undercuts at the interface grey iron/cast aluminium alloy.

Grey cast iron liners with rough outer surfaces using either directly the as-cast surface (left) or a subsequent surface treatment (aluminium spraying) (right) ensure improved mechanical bonding

Source: KS ATAG

Micrograph demonstrating mechanical bonding between the cast aluminium alloy and the grey iron liner with a rough surface

Source: VAW

Another option to ensure a good basis for the cast-in operation is to use a thin-walled grey iron tube which is pre-coated with a thermally sprayed aluminium layer for improved bonding.

3.3.2 Monolithic aluminium concept (ALUSIL®)

Hypereutectic AlSi alloys (AlSi17Cu4Mg, e.g. ALUSIL®) can be used to produce monolithic aluminium engine blocks. During solidification, primary Si particles are precipitated which – after an appropriate machining and honing procedure – protect the cylinder bore surfaces in the form of small wear resistant grains and directly provide the required tribological surface characteristics for a proper operation of the engine.

The advantages of this solution are:

- Low weight (no grey cast iron cylinder liners necessary)
- Compact cylinder block design (no liners, minimum spacing between bores: 4 mm)
- High thermal conductivity (no gap)
- Low distortion (minimum residual stresses)
- Small assembly tolerances for pistons (similar thermal expansion coefficient as piston material)
- Easy recycling (no extraneous material).

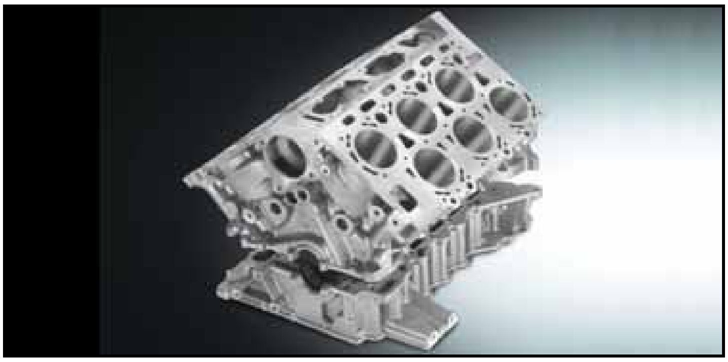
However, according to the present state-of-the-art, this alloy can only be cast using the LPDC (Low Pressure Die Casting) process due to the following limitations:

- High pouring temperature
- Large solidification interval
- Segregation and inhomogeneous distribution of primary silicon particles.

Hypereutectic AlSi alloys ask for relatively low impurity element limits and are therefore mainly used for high performance gasoline engines, but much less in the mass market of in-line four cylinder engines.

V8 gasoline engine (BMW M5) made from ALUSIL®

Source: Kolbenschmidt



W12 gasoline engine (VW) made from ALUSIL®

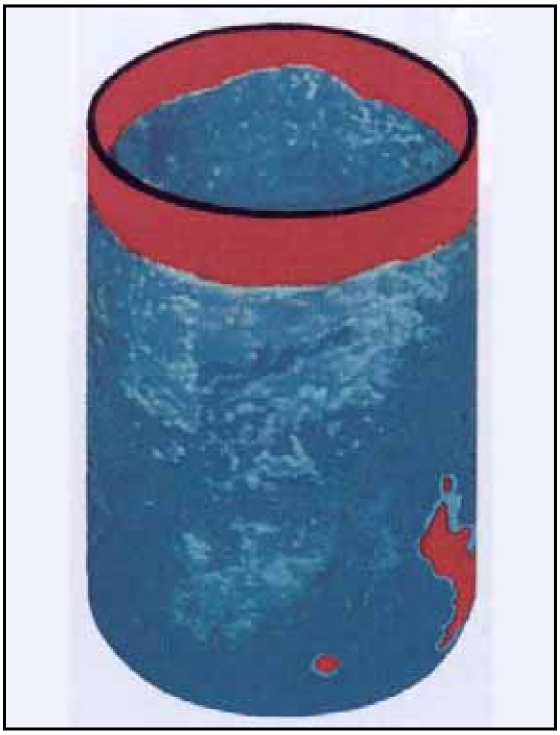
Source: Kolbenschmidt

3.3.3 Heterogeneous concept: Cast-in aluminium cylinder liners (SILITEC® and ALBOND®)

Wear-resistant cylinder liners which consist of a hypereutectic AlSi alloy were developed by PEAK Werkstoff GmbH as a lightweight alternative to the considerably heavier cast iron cylinder liners, but also as an alternative to the relatively expensive monolithic engine block made from the hypereutectic primary AlSi17Cu4Mg (ALUSIL®) casting alloy. The cylinder liners can then be cast-in, preferentially using the high pressure die casting process with a lower cost (secondary) AlSiCu casting alloy.

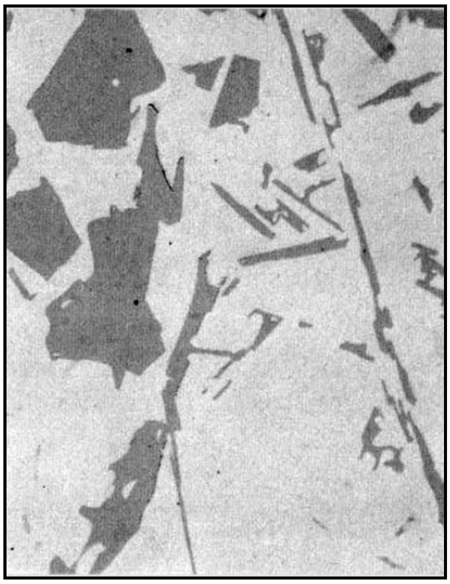
The SILITEC® hypereutectic liner materials are produced by spray compaction; the spray-compacted ingots are subsequently extruded. The high solidification rate of the spray compaction process leads to significantly smaller primary silicon particles than in standard casting processes and ensures excellent tribological properties of the liner surface after the special honing process. Since the same base material is used, metallic bonding between the liner and the engine block is achieved over more than 50% of the contact surface. The result is an engine block showing low distortion and high dimensional stability.

Aluminium-based cylinder liners are most suitable for high pressure die casting where melting-through is avoided because the thermal energy of the molten aluminum is removed rapidly through the metal die. Other casting processes such as sand, semi-permanent mold and low-pressure die casting have longer solidification times, leading to the transfer of additional thermal energy to the aluminium liners. This additional energy may result in localized melting and deformation of the liner. Thus, in order to use aluminium cylinder liners in casting processes other than HPDC, it becomes necessary to develop alloys that are more resistant to residual heat in the casting process.

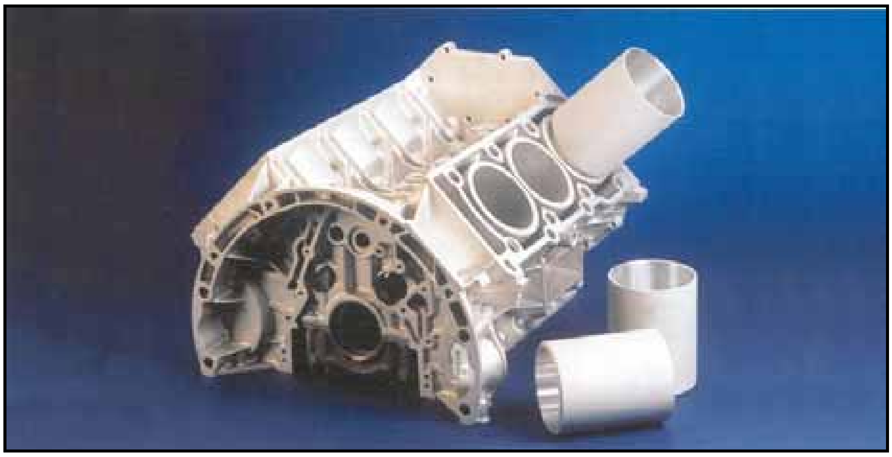


Ultrasonic scan showing areas of good (blue) and bad (red) metallic contact

Source: PEAK/Daimler

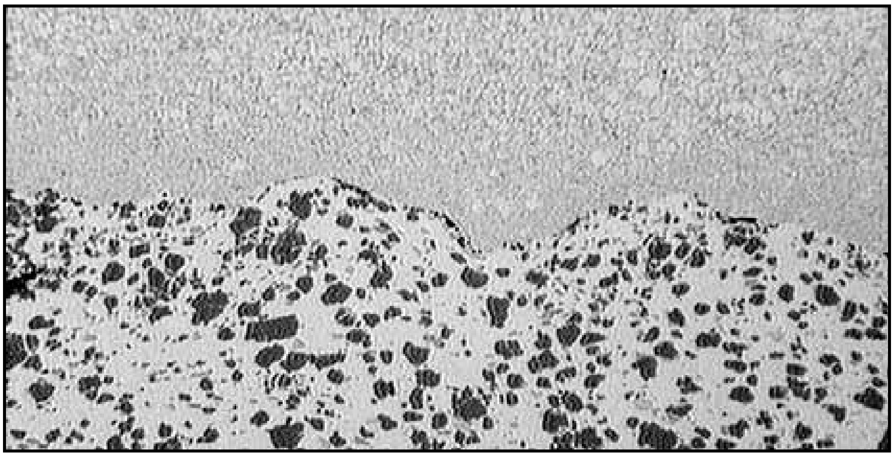


Micrograph showing as-cast microstructure of hypereutectic AlSi17Cu4Mg alloy



V6 gasoline engine block (Daimler) with SILITEC® liners

Source: PEAK



Micrograph showing interface between SILITEC® liner and the cast engine block

Source: PEAK

ALBOND® (developed by MAHLE) is another solution particularly suited as a cast-in material for aluminium die cast engine blocks. Cylinder liner compounds are separately cast using hypereutectic AlSi alloys and later cast-in into the engine block. The distance between the cylinders can be reduced, a more compact engine design is made possible, and, depending on the design of the cylinder liners, the weight can be reduced by up to 400 grams per cylinder compared to cast iron liners. The specially roughened exterior surface ensures an even form-fitting bond when the aluminum alloy of the engine block is cast around the cylinder liners.

The improved bond of the rough ALBOND® surface contributes to more effective and uniform cooling of the cylinders during engine operation, i.e. reduced cylinder distortion, lower oil consumption, and minimized frictional losses. Engine blocks manufactured with ALBOND® are also noted for improved recyclability because separation of the cylinder liners from the engine block is no longer required. A special honing process results in a finer surface and a greater wear resistance.

ALBOND® aluminum rough cast cylinder liner compound

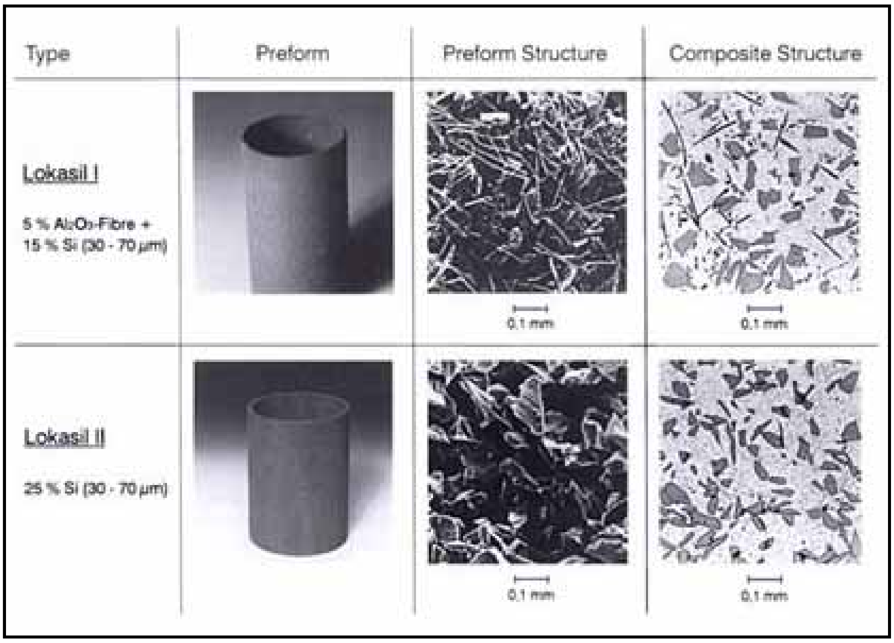
Source: Mahle

3.3.4 Quasi-monolithic concept: Infiltrated pre-forms (LOKASIL®)

In order to avoid the disadvantages arising from the use of hypereutectic alloys for the entire engine block (leading to additional material and processing cost), the LOKASIL® concept was developed which provides an appropriate microstructure where it is locally needed (quasi-monolithic concept).

The gapless insertion of the composite material is achieved by the infiltration of highly porous, hollow cylindrical pre-forms made of ceramic fibres and silicon particles (LOKASIL® I) or only silicon particles (LOKASIL® II) with an aluminium alloy during the engine block casting process. Different types of ceramic fibres can be used in case of extreme operating conditions (e.g. minimum distance between the cylinders and/or elevated component temperatures).

Generally applied today is the LOKASIL® II variant which satisfies all technical requirements. The porous pre-forms with 25 vol. % of Si particles (30 – 70 µm) are produced by gel-freeze-casting, subsequently sintered and then infiltrated with a hypoeutectic casting alloy made from recycled aluminium. The squeeze casting process is used to produce the engine block as it provides both, slow mould filling and high pressure for proper infiltration. The holistic development approach included the application of a special finish honing process to produce the tribologically optimised surface.



LOKASIL® (I + II): pre-form and composite structure

Source: KS ATAG

LOKASIL® technology: Silicon perform (left) and local silicon enrichment of the cylinder bore surface (right)

Source: KS ATAG

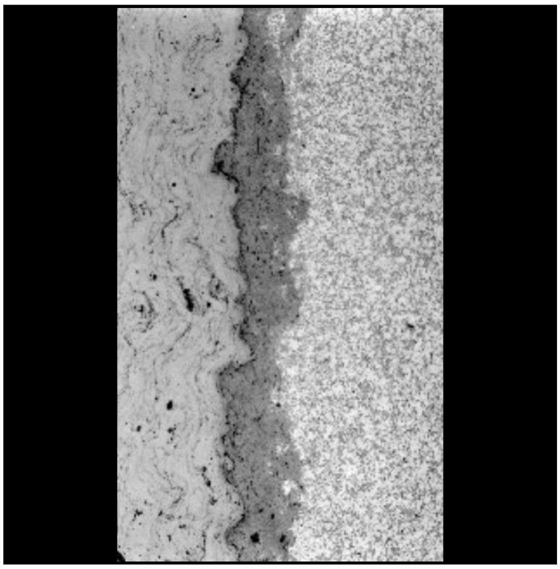
Attempts are currently made to achieve good infiltration with the highly productive HPDC (High Pressure Die Casting) process as well.

3.3.5 Heterogeneous concept: Thermally sprayed inserts (GOEDEL®)

The idea of this concept is to keep the well-known tribological properties of grey iron and – at the same time – to solve the existing technical issues lack of contact and gap formation, which lead to problems with heat extraction and dimensional stability, of the traditional grey iron liner solution.

In the GOEDEL® concept, an iron layer is thermally sprayed onto a cylindrical base geometry followed by a layer of an appropriate AlSi alloy, creating a well defined and gap-free transition from iron to aluminium. The micro-roughness of the outer aluminium surface ensures a good metallic bonding during casting-in of the liner, especially when the HPDC process is applied.

The benefit of the metallic bond is a better heat flow and a higher stiffness (+30%) of the liner-block compound resulting in a lower distortion of the cylinder bore and thus in lower blow-by, oil consumption and wear. The multi-layer can also be tailored according to the specific needs of tribology and castability.



Micrograph of the transition zone between the thermal sprayed multi-layer and the aluminium casting alloy

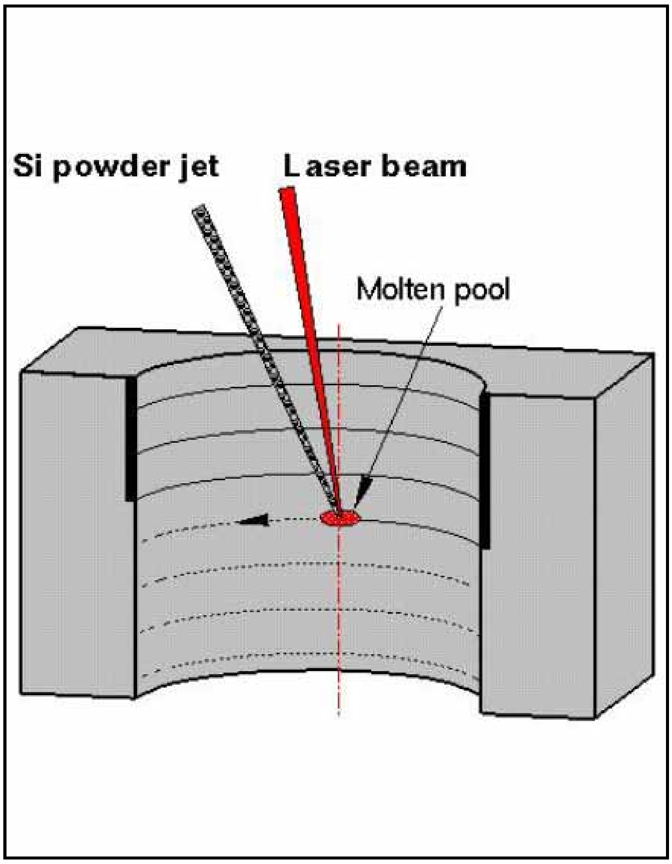
Source: Federal Mogul

3.3.6 Quasi-Monolithic Concept: TRIBOSIL®

The ideal solution would be a monolithic all-aluminium block made of easy-to-cast, cost-efficient aluminium alloys, whereby the high stability and good heat dissipation in the inter-bore area is achieved in a second process step. Such a solution is offered by the TRIBOSIL® concept where required liner surfaces are created by means of laser alloying of the original gravity cast engine blocks made from conventional secondary casting alloys. The original cast aluminium matrix of the cylinder bores is locally enriched with homogeneously distributed, fine silicon particles (diameter < 10 µm) to create a “hypereutectic” surface structure.

In the laser alloying process, a moving laser beam locally melts the cylinder surface. Simultaneously, silicon powder is injected into the melt pool which describes a helical movement. Layers with a thickness of about 600 µm are achieved revealing an optimum structure and distribution of primary silicon particles resulting in high hardness and excellent tribological properties after appropriate honing. The TRIBOSIL® liner surfaces offer good thermal conduction and the ability to realize engine blocks with small inter-bore distances.

The disadvantage of this process is the relatively long treatment time of 3 – 6 min, which is significantly higher than the standard cycle time of a typical engine production line.



Laser alloying of a cylinder bore (schematic)

Source: VAW

Cut through the wall of a laser alloyed cylinder

Source: VAW

Hypereutectic layer with gap-free transition zone towards the matrix alloy (AlSi9Cu3)

Source: VAW

Structure of the laser-alloyed surface after recessing of the matrix by means of honing

Source: VAW

3.3.7 Cylinder liner solutions with surface coatings

Today, a wide range of surface coating technologies is available and there are many different wear-resistant materials or material combinations which are valid candidates for surface coating. Consequently, lots of methods have been examined or are actually applied for the surface treatment of aluminium cylinder bores. Some examples are:

NIKASIL® and GALNICAL®

These designations refer to galvanic coating processes which result in a Ni-SiC dispersion layer (containing about 10% SiC particles with a diameter of 1-3 µm embedded in a nickel matrix). Galvanic deposition is a proven technology, however, it requires a very low porosity in the as-cast surface. Both NIKASIL® and GALNICAL® are used in series production. However, environmental issues due to the presence of nickel and problems with corrosion of the galvanic layer due to sulphur-containing fuels have significantly limited their application.

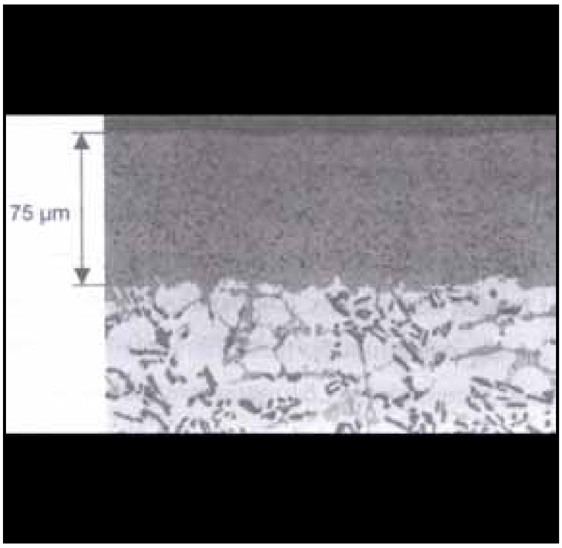
Plasma coating (ROTAPLASMA®)

The atmospheric plasma spray process can apply by far the widest variety of coating materials of any thermal spray process. The flexibility of the plasma spray process is based on its ability to develop sufficient energy to melt almost any coating feedstock material in powder form. The feedstock material is injected into the hot plasma plume, where it is melted and propelled towards the target substrate to form the coating.

Spraying of engine block cylinder bores

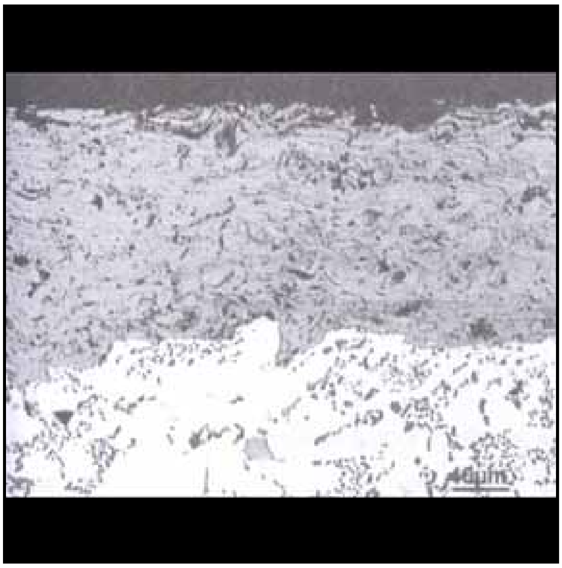
Source: Sulzer Metco

The development of this process has advanced so far that gasoline and diesel engines are now in series production with atmospheric plasma coated cylinder surfaces. Good results were achieved using Fe as a coating material. Furthermore, FeO and Fe_3O_4 can be dispersed in the layer acting as a solid lubricant such as graphite in grey iron



Micrograph showing Ni-SiC dispersion layer

Source: Kolbenschmidt



Micrograph showing plasma coating layer

Source: Sulzer-Metco

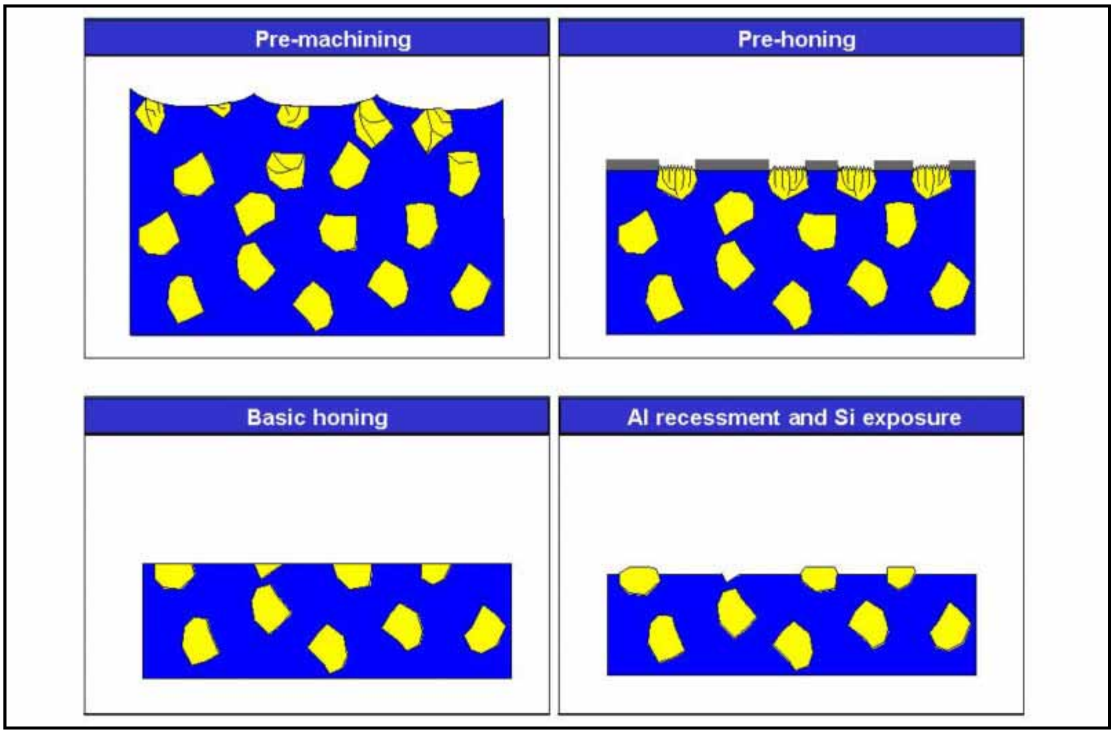
Other applicable methods include laser coating of an AlSi alloy, physical (PVD) and chemical vapour deposition (CVD), etc., using materials such as diamond-like carbon (DLC), chromium nitride, titanium nitride, i.e. many different surface coating structures and chemistries.

3.3.8 Honing of hypereutectic AlSi surfaces

The various cylinder liner manufacturing technologies based on hypereutectic AlSi alloy compositions (ALUSIL®, SILITEC®, etc.) rely on the presence of a dense distribution of hard, primary silicon particles which act as the tribological partners for piston and piston rings. The technical requirements like low friction, high stability and good lubrication under dry sliding conditions can only be met by the presence of an appropriate surface topography. This structure is created by a special honing process which is different from the conventional honing of grey cast iron. Honing of hypereutectic AlSi surfaces usually requires the following steps:

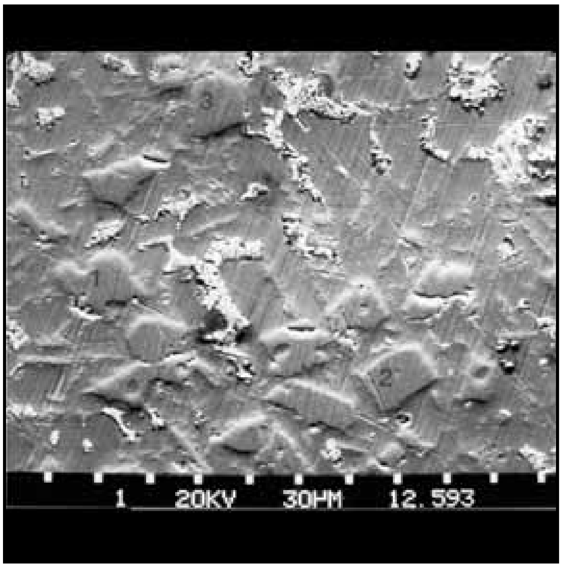
- A pre-honing step corrects the cylinder shape and removes most of the damaged surface layer resulting from pre-machining.
- In the following base-honing step, the final surface shape of the primary silicon particles is created.
- Subsequently, a recessing of the aluminium matrix and an exposure of the silicon particles is carried out providing both hard particles to withstand the sliding wear of the piston and to provide oil reservoirs for good distribution of the lubricant. For this honing step special tools are used with the abrasive particles being smaller than the Si particles and embedded in a soft matrix.

Compared to recessing by etching, this technique provides smooth particle edges which prevent break-outs.



Honing steps for hypereutectic AlSi cylinder surfaces

Source: Nagel



SEM-Micrograph showing the final surface after honing with recessed Al matrix and exposed Si particles

Source: Gehring

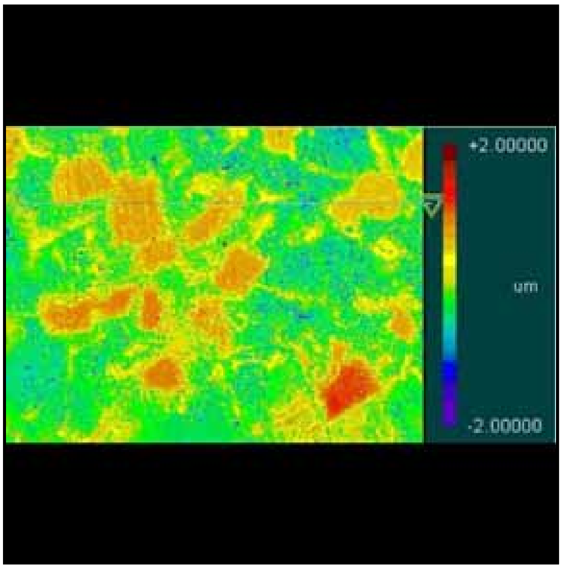


Image from white light interference microscope showing the topography of the final cylinder surface

Source: VAW

3.4 Outlook

Further optimization of cylinder linings in aluminium engine blocks requires a holistic approach. Significant development steps are foreseen in particular with respect to optimised surface treatment/coating technologies. Other development topics include technologies to:

- Produce the “perfect” engine bore: Traditionally, cylinder bores are machined and honed in a cold cylinder block with no stresses or thermal loads. Once assembled, operating and hot, engine bores are far from being a true cylinder in most cases. Efforts are now underway to produce the perfect engine bore by designing and machining a non-cylindrical bore at the machining stage that becomes perfectly cylindrical when the engine is assembled and running at normal operating temperatures.

- Laser-etch liner surfaces: A proper control of the micro-topography of the sliding surfaces helps the surfaces retain the lubricant and allow even lower viscosity lubricants to be employed.

Furthermore, lubricants were originally designed for cast iron engines and steel components. The expectation that a lubricant developed for ferrous surfaces will operate just as effectively on nonferrous surfaces may well be wrong. While sulphur levels in fuels have been reduced dramatically, reports from the field suggest that some of the new nonferrous aluminium-silicon engine materials are exhibiting different kinds of wear issues in some circumstances.

Another topic is the detrimental effect of ethanol blends and FAME (fatty acid methyl ester) based biofuels. Biodiesel components are not as stable as the lubricant and will eventually deteriorate through oxidation, creating gums and deposits and changing the viscosity profile of the oil. The incompatibilities between biofuels and engine materials can cause leaching or corrosive wear of the metal surfaces. Ethanol also increases water solubility in oil, which can lead to internal corrosion of some engine components. In addition, as the ethanol oxidizes in a high-temperature environment, aggressive chemicals such as aldehydes and acids can occur and then act as powerful corrosives on engine components.

These examples show that the substitution of a material by another material in a complex system such as an internal combustion engine is not a simple task but requires a close review and redefinition of the whole system.