lubricants

IMPACT FACTOR 3.6

CITESCORE 5.6

Review

Application of Al–Si Alloys in Internal Combustion Engines

Saša Milojević, Slavica Miladinović, Sandra Gajević, Stefan Čukić and Blaža Stojanović

Special Issue
Tribological Characterization and Optimization of Aluminum-Based Composites for Powertrain Systems

Edited by
Dr. Saša T. Milojević and Dr. Slavica Miladinovic

MDPI

https://doi.org/10.3390/lubricants14070277

lubricants

MDPI

Review

Application of Al–Si Alloys in Internal Combustion Engines

Saša Milojević, Slavica Miladinović, Sandra Gajević, Stefan Čukić and Blaža Stojanović *

Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia; sasa.milojevic@kg.ac.rs (S.M.); slavicam@kg.ac.rs (S.M.); sandrav@kg.ac.rs (S.G.); stefan.cukic@kg.ac.rs (S.Č.)
* Correspondence: blaza@kg.ac.rs

Abstract

The use of aluminium alloys in internal combustion engines is an effective strategy for increasing energy efficiency, reducing component mass, and lowering harmful gas emissions. This paper analyses different types of Al–Si alloys (hypoeutectic, eutectic, and hypereutectic) in the context of their use in the production of engine blocks, pistons, and cylinder liners. Special attention is given to the tribological challenges of using aluminium, such as increased wear and lower strength compared to traditional materials such as cast iron. Modern methods for improving wear resistance are discussed, including alloying, the application of solid lubricants and protective coatings (Ni–SiC, Al_2O_3, MoS_2, etc.), and advanced surface engineering technologies such as PTWA, HVOF, and laser alloying techniques. This paper also presents practical examples of industrial applications, highlighting their essential role in the development of lightweight, high–performance internal combustion engines. This review highlights that the combination of optimized alloy composition and advanced surface engineering technologies represents the most effective approach for enhancing the durability and tribological performance of lightweight engine components.

Keywords: Al–Si alloy; internal combustion engine; coatings; application

1. Introduction

The application of new methods for producing internal combustion (IC) engine parts and related equipment increases operational reliability and reduces fuel consumption in motor vehicles, thereby lowering exhaust gas emissions. Reducing component weight through the use of aluminium and other light metal structures is one example of optimization. Fuel consumption decreases in parallel with vehicle weight reduction, which is achieved by using aluminium components.

The use of aluminium alloys in IC engines has become a key factor in improving performance, reducing weight, fuel consumption, and emissions. Aluminium based alloys are widely applied in the manufacture of components such as IC engine block, piston, cylinder head, and other parts, thanks to their excellent mechanical and tribological properties.

Weight reduction of motor vehicle components is a crucial step in enhancing energy efficiency. Studies have shown that reducing a vehicle's weight by 10% not only increases material efficiency but can also lower fuel consumption by 4–8% [1] or 6–8% [2–4]. It has also been demonstrated that reducing vehicle weight by 100 kg decreases CO_2 emissions by approx. 9 g/km, while lightweight components contribute significantly to higher overall energy efficiency [5–7].

Despite these advantages, the use of aluminium in IC engines presents specific challenges, including relatively low wear resistance and lower mechanical strength compared

Check for updates

Received: 12 June 2026
Revised: 27 June 2026
Accepted: 16 July 2026
Published: 21 July 2026

to conventional materials such as cast iron. Under normal operating conditions, mechanical friction can consume between 4 and 15% of the total fuel energy, thereby reducing efficiency. The majority of this friction originates from three key systems: the piston–ring–cylinder liner assembly, the crankshaft and bearing system, and the valve–train. Notably, the piston assembly alone may contribute up to 26% of total frictional losses [8]. These challenges can be addressed by employing different alloys, coatings, and composites that improve the tribological and mechanical properties of aluminium alloys.

The application of modern methods for producing IC engine parts significantly contributes to operational reliability and reduced fuel consumption in motor vehicles. Design optimization through the use of aluminium alloys enables not only weight reduction but also improved mechanical and thermal properties of components. This results in lower mechanical losses inside IC engines, enhanced combustion efficiency, and reduced exhaust gas emissions, which is particularly important in light of increasingly strict environmental regulations. Replacing cast iron and steel with aluminium alloys represents a major step in this optimization. Due to their favorable mechanical, thermal, and tribological characteristics, Al–Si alloys play a central role in IC engine applications.

The use of aluminium alloys in vehicle engines represents one of the most effective ways to increase efficiency and reduce the environmental impact of transportation. This paper will provide a detailed analysis of the different types of Al–Si alloys, their properties, and their applications in the automotive industry, with particular attention to examples of vehicles that employ these materials in their IC engines.

While many review papers focused specifically on various categories, such as aluminium alloys, tribological coatings or lightweight materials and engine manufacturing technologies, up to date no attempts have been made for a broad study of hypoeutectic, eutectic, and hypereutectic Al–Si alloys in the design of internal combustion engine components. The present review possesses the novelty of being centred around a single framework in that successive sections cover alloy classification, tribological challenges, manufacturing technologies, surface engineering approaches, and industrial applications. In addition, trench and new development directions are systematically compared for the most practical examples from automotive, aerospace and marine industries.

2. Al–Si Alloys

Aluminium alloys offer several advantages over traditional materials such as steel and cast iron [9]:

- Low density (2.7 g/cm^3): only one third the density of steel, allowing a significant reduction in IC engine weight.
- Non–ferromagnetic properties.
- Corrosion resistance: aluminium forms a very thin (about 5 nm) transparent oxide film that protects the surface from corrosion, thereby extending component service life.
- High thermal conductivity: facilitates efficient heat dissipation and reduces the risk of IC engine overheating.
- Non–flammability and non–toxicity.
- Good machinability and castability: enabling the production of complex shapes at lower cost.
- Alloying flexibility: the addition of elements such as Si, Cu, Mg, and Ni improves mechanical and tribological properties.

In modern IC engines, an increasing number of cast–iron parts are being replaced with aluminium alloy components. Research indicates a continuous rise in the use of aluminium for IC engine applications. A comparison of the number of publications on Al–Si alloys and grey cast iron in IC engines, as indexed by Google Scholar [10], is presented in Figure 1.

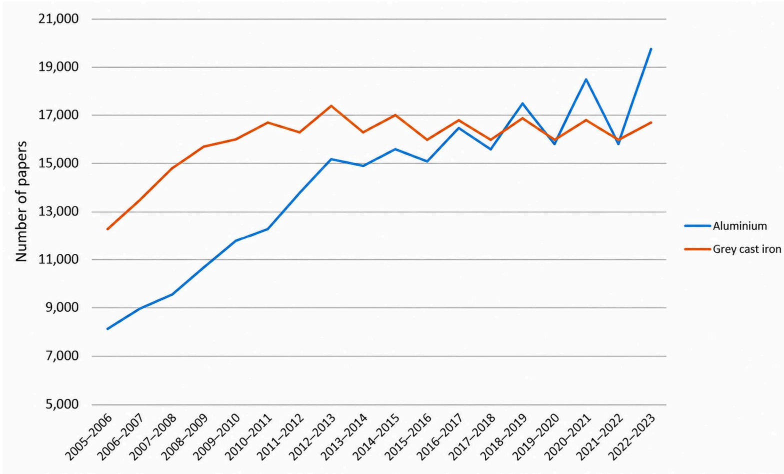


Figure 1. Comparison of the number of papers on Al–Si alloys and grey cast iron applications in IC engines based on Google Scholar searches (period: 2005–2023; search performed by the authors) [10].

The growing use of Al–Si alloys in IC engines and vehicles in general is driven by several key factors:

1. Regulatory requirements—CO_2 emission standards are pressuring manufacturers to reduce fuel consumption and vehicle weight, encouraging the use of lighter materials such as aluminium. For example, the EU set a target for average CO_2 emissions from new cars of 95 g/km by 2021. These regulatory limits are a major driver behind the shift toward lightweight aluminium components [11].
2. Technological developments—Advances in alloy design and manufacturing methods have enabled aluminium components to achieve improved mechanical properties, such as higher strength and wear resistance, making them increasingly suitable for demanding automotive applications.
3. Cost–effectiveness—Although aluminium is more expensive than cast iron, the total cost of ownership can be reduced through lower fuel consumption and longer component life. Studies indicate that reducing vehicle weight by 10% can lead to a 3–7% reduction in fuel consumption, which directly contributes to overall vehicle economy [12].

In addition, the growing use of aluminium is strongly influenced by the rapid development of electric vehicles (EVs), as these alloys are applied not only in IC engines but also in battery housings, vehicle structures, and cooling systems, etc. [12–18].

The addition of Si to pure Al produces an alloy with a reduced melting point and increased fluidity, which is not heat treatable. Such alloys are used for castings and as filler wires in fusion welding. Depending on the Si content, three groups can be distinguished:

1. Hypoeutectic alloys with less than 12 wt.% Si.
2. Eutectic alloys with about 12–13 wt.% Si.
3. Hypereutectic alloys with more than 13 wt.% Si.

In Al–Si alloys, the Si content directly affects hardness, machinability, castability, and wear resistance (Table 1). Adding a small amount of Mg produces the Mg_2Si phase, resulting in a heat–treatable alloy strengthened by thermal precipitation. The modification of Si morphology can also be achieved by adding Na to hypoeutectic and eutectic alloys, and P to hypereutectic alloys.

Applications vary with composition: alloys containing up to 12 wt.% Si are used as coatings for soldering sheet metal and can be produced by forging, while components exposed to wear are mainly manufactured from cast hypereutectic Al–Si alloys. Most Al–Si alloys also contain Fe, Mg, Cu, and Mn. Active research is ongoing on Al–Si–Fe alloys to improve their tribological behavior.

Different alloying elements provide specific benefits:

1. Cu enhances wear resistance and enables aging/precipitation hardening through the formation of $AlCu_2$ phases.
2. Mg and Cu together increase strength but reduce ductility and corrosion resistance.
3. Mn improves high–temperature performance and modifies the Al–Fe–Si phase morphology.

Ni, P, Ca, Sr, and others are added for further structural modification. In particular, P and/or Sr refine primary Si in hypereutectic alloys, while Sr or Na at lower Si contents and under rapid cooling can promote the formation of primary Al dendrites. As a result, alloys with 12–14 wt.% Si may solidify as hypereutectic under slow cooling without modifiers, or as hypoeutectic under rapid cooling with Sr or Na [8,19–22].

High Fe content is undesirable, as it leads to the formation of brittle, hard inter–metallic phases. This drawback can be mitigated by adding Ni, Be, Zr, Mn, Co, Sr, Ca, or Re, which alter the morphology of lamellar inter–metallic and thereby improve mechanical performance. Wear resistance remains one of the most important characteristics of Al–Si alloys. In addition to chemical composition, their properties strongly depend on the fabrication method. Hardness, tensile strength, brittleness, and microstructure all play critical roles in determining wear behaviour [23].

Table 1. Characteristics and application of Al–Si alloy by Si content [9,24–27].

Si Content (%)	Characteristics
<5%	Low wear resistance, suitable for structural parts.
5–10%	Good strength, used for cylinder heads and IC engine blocks.
12–13%	Optimal balance of strength and wear, used for pistons.
>14%	High wear resistance, used for cylinder liners.

Although aluminium alloys offer numerous advantages for IC engine components, their relatively lower strength and wear resistance compared to steel and cast iron present technical challenges. These limitations can be mitigated through alloying, the introduction of structure modifiers, and various surface protection methods, including heat treatment and the application of nickel–plated or composite coatings [23,28].

Recent research highlights the significance of Ni–based coatings (e.g., Ni–SiC, Ni–GO (Nickel–Graphene Oxide), Ni–Al_2O_3, Ni–WC) in enhancing wear resistance and mechanical durability of engine components [29,30]. Additionally, hybrid techniques such as high–velocity oxy–fuel (HVOF) spraying and plasma spraying provide coatings with high stability under elevated temperatures and dynamic loads [31].

2.1. Surface Modification and Coating Technologies for Al–Si Alloys

The tribological and mechanical performance of engine components can be enhanced through the application of coatings made from various materials. This approach also addresses the increased wear and lower strength of IC engine cylinders in motor vehicles.

Coatings have long been employed in diesel engines to provide thermal insulation for the combustion chamber, including the piston bowl and cylinder liners. By thermally insulating these components, coatings help reduce fuel consumption, improve IC engine efficiency, and facilitate cold starting. The primary goal of such coatings is to minimize heat losses by preventing the transfer of heat from the working fluid to the cylinder liners. As a result, the combustion chamber walls maintain elevated temperatures, reducing the temperature difference between the walls and the working fluid during combustion.

https://doi.org/10.3390/lubricants14070277

However, thermal insulation coatings have some limitations, including durability and reliability during service life, as well as potential degradation or delamination from the substrate material.

Iron–based coatings are particularly effective for insulating diesel engine cylinders made of aluminium blocks and pistons. The thermal conductivity of iron–based coatings containing 22–40% aluminium depends on temperature and is roughly ten times lower than that of eutectic Al–Si alloys. Furthermore, coatings with iron impurities exhibit coefficients of thermal expansion similar to those of eutectic and hypoeutectic Al–Si alloys, making them compatible with the materials used in pistons and IC engine blocks.

The incorporation of iron into coating materials addresses the issue of residual surface stresses after heat treatment, which can otherwise lead to cracking between the coating and the substrate. Compared to purely ceramic coatings, iron additions reduce the coefficient of thermal expansion while providing a combination of favorable mechanical properties, low density, cost–effectiveness, and enhanced resistance to corrosive agents such as sulfuric acid. Additionally, the availability of iron and aluminium raw materials represents a practical advantage.

Iron–based tribological coatings are particularly suitable for sliding surfaces, such as the cylinder liners of diesel engines. Over time, monolithic cast iron blocks have been replaced with blocks based on Al–Si alloys containing 17–20 wt.% Si. This transition has improved tribological performance due to reduced wear on the inner sliding surfaces of the cylinder liners [32].

Using cast iron liners to enhance strength and tribological properties is problematic in terms of weight reduction. The added thickness of the liner requires larger cylinder diameters, which increases overall engine dimensions. For small cylinders, such as those in two–stroke engines for generators, pumps, or chemical compressors, the use of liners is often impractical.

A more feasible approach involves applying surface protection directly to aluminium alloy cylinders without liner inserts. This can be achieved using thin–film coatings with superior mechanical and tribological properties or via chemical and thermal treatments of the sliding surface. Techniques include galvanization and thin–film coatings based on chromium or nickel. However, environmental regulations increasingly restrict these methods due to the health risks of chromium and nickel micro–particles entering the piston space, exhaust system, or environment.

Thermal spray methods, such as plasma spraying, provide a modern solution for applying protective coatings. Plasma spraying under atmospheric conditions has been commercialized and demonstrates excellent coating characteristics, including metallography, micro–hardness, tensile strength, and machinability [33].

In single–cylinder IC engines and aluminium alloy air compressors, issues such as cracking and delamination of iron–based coatings have been observed. Coating microstructures are typically lamellar, containing particles of molten powder and oxide layers—a common feature of thermal spray processes. Plasma spraying allows uniform distribution of the coating, and subsequent post–treatment can prevent cracking and delamination and reduce friction and wear [34,35].

These findings highlight the importance of tribological optimization for aluminium alloy IC engine cylinders and reciprocating air compressors. Such optimization reduces mechanical energy losses, fuel consumption, and consequently, exhaust emissions [36,37].

Despite challenges related to wear and lower strength, aluminium remains a promising material for IC engine components. Wear resistance can be enhanced through reinforcements in aluminium based composites. Common reinforcements include graphite, silicon carbide (SiC), and aluminium oxide (Al_2O_3).

The effect of reinforcement on strength and wear resistance depends on its type and content. Higher fractions of SiC and Al_2O_3 increase strength and mechanical performance, while graphite improves tribological characteristics. By carefully combining reinforcements, optimal tribological and mechanical properties of aluminium alloys can be achieved.

2.2. Methods for Manufacturing Cylinders and Pistons of Internal Combustion Engines and Compressors from Aluminium–Based Composite Materials

The use of aluminium instead of cast iron for manufacturing IC engine blocks and reciprocating air compressor cylinders primarily contributes to weight reduction. The use of Al–Si alloys also lowers casting production costs, allows complete recyclability, eliminates corrosion, and improves heat transfer through the material surface.

Al–Si alloys, as described above, can be classified according to their silicon content: hypoeutectic (less than 12% Si), eutectic (12–13% Si), and hypereutectic (more than 13% Si). They can also be categorized based on structure, which affects properties such as the melting point [38].

Eutectic alloys have a precise component ratio that forms a eutectic point, where the material solidifies at a specific temperature and contains two or more phases. Al–Si eutectic alloys are widely used in IC engines due to their excellent machinability and corrosion resistance.

Hypoeutectic alloys contain less of one component compared to the eutectic composition. These alloys solidify over a temperature range above the eutectic temperature and are generally characterized by good castability and machinability. During cooling, a primary phase may form before the eutectic temperature is reached.

Hypereutectic alloys contain a higher proportion of one component than the eutectic point. Solid phases may form prior to the eutectic state, which influences mechanical properties. These alloys are often employed in demanding applications, such as IC engine parts requiring high strength and wear resistance.

In IC engines, Al–Si alloys are used for components including pistons, cylinder heads, and engine cases. Alloy selection depends on requirements for weight, strength, corrosion resistance, and operating temperature. Eutectic alloys are often preferred for their balance of strength and machinability, while hypo and hypereutectic alloys are chosen when enhanced mechanical properties are needed.

Poor tribological performance of aluminium can lead to deformations and accelerated wear in sliding components. These issues are typically addressed through surface treatments. The tribo–mechanical system of the cylinder liner piston assembly requires both strength and wear resistance, which is critical for the sliding surfaces made from Al–Si alloys.

To improve lubrication, cylinder contact surfaces are often honed to create micro–textures. However, during operation, piston rings can squeeze lubricant out of these grooves, as lubrication is not limitless, leading to increased friction and wear.

Increasing IC engine power and torque partly depends on improving combustion efficiency. Optimizing the combustion process requires higher maximum pressures in the cylinder, which raises thermo–mechanical loads on the cylinder and related components. Concurrently, modern fuel–saving technologies, such as low–viscosity oils, start–stop systems, reduced engine displacement, variable valve timing (VVT), high–pressure fuel injection, and variable compression ratios (VCR), further increase the load and wear on the cylinder–piston assembly [36,37].

Modern IC engine blocks must withstand higher maximum cylinder pressures and increased thermo–mechanical loads. At the same time, they are required to be lightweight and resistant to fuels of varying chemical aggressiveness.

The casting process for IC engine blocks has become increasingly complex due to the integration of connection points and the installation of engine components that perform secondary functions in the vehicle. These include mounting points for peripheral devices such as junction boxes, gearboxes, flywheel housings, and water pump housings. Additionally, channels for oil flow in the lubrication system and for forced circulation of the cooling fluid are cast directly into the block.

Given these increasingly stringent requirements, classical manufacturing technologies alone are no longer sufficient for producing IC engine blocks. This also applies to the machining of sliding surfaces and the fabrication of cylinder liners.

Figure 2 presents an overview of the technologies used for producing IC engine blocks and processing cylinder liners. Engine blocks are typically manufactured as monolithic (one–piece) units or using pressed cylinder liners in a mixed–type design.

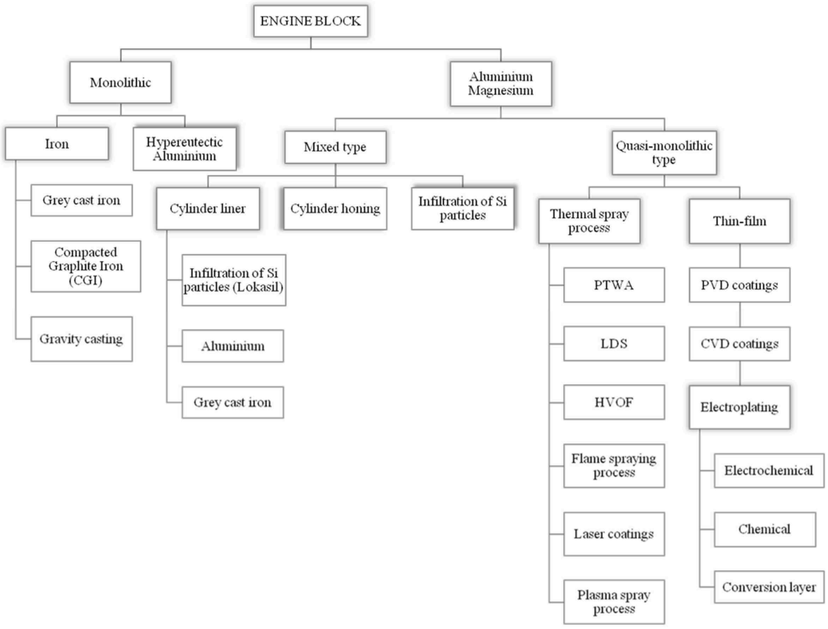


Figure 2. Systematic Overview of Technologies for Manufacturing Blocks and Processing Cylinder Liners in IC Engines and Reciprocating Compressors.

Although Figure 2 includes general manufacturing technologies used in engine production, the presented routes are widely employed for the manufacturing and surface engineering of Al–Si engine blocks and cylinder liners.

Monolithic aluminium engine blocks for IC engines are typically made from the expensive hypereutectic Al–Si alloy $AlSi_{17}Cu_4Mg$, commercially known as Alusil, containing more than 13 wt.% Si. Alusil exhibits excellent tribological properties due to its silicon particle content.

Mixed–type IC engine blocks are also made of Al–Si alloys that are not inherently wear–resistant but are reinforced with cylinder liners made of materials with superior tribological characteristics. Aluminium blocks may be fitted with liners made of grey cast iron or Al–Si alloys. Gray cast iron demonstrates favorable tribological behaviour due to its paralytic microstructure and lamellar graphite, with graphite acting as a solid lubricant on unlubricated or boundary–lubricated surfaces. Further reduction of friction in the cylinder liner is achieved by honing the sliding surface.

In mass production, aluminium IC engine blocks with grey cast iron liners are more cost–effective and exhibit better friction and wear performance than blocks with monolithic silicon particle surfaces or mixed type Al–Si liners.

The hypereutectic cylinder liner material Silitec can be further enhanced through a spray process, which applies fine silicon particles to the surface followed by honing, improving tribological performance and strength.

The Lokasil technology involves producing blocks in two stages. First, blocks are cast from a less expensive Al–Si alloy using high–pressure casting. Then, compression casting is performed with cylindrical porous inserts, and silicon particles are infiltrated into the surface layer, locally creating a hypereutectic Al–Si alloy.

As previously noted, the increased structural loads on IC engine blocks reduce their dynamic load–bearing capacity. This issue can also be addressed using a third–generation quasi–monolithic aluminium block, which combines a cost–effective monolithic Al–Si base structure with coatings applied to the cylinder liner surface [32,39].

Nikasil from Mahle and Chromal are electroplated thin–film coatings. In these technologies, dispersion layers of Ni–SiC or Cr are deposited onto porous surfaces through the electroplating process. Incorporating hard SiC particles into the nickel matrix provides these coatings with high hardness, excellent adhesion, and superior abrasion resistance. These coatings enable aluminium engine blocks to operate without conventional cast–iron liners while maintaining satisfactory tribological performance. However, electroplating processes require strict control of bath chemistry and waste treatment due to increasingly restrictive environmental regulations associated with nickel–based plating [40–42].

Thermal coating methods include the electric arc spray process with a single PTWA (Plasma Transferred Wire Arc) wire or with two DAG–LDS (Twin–Wire–Arc; German: Lichtbogendrahtspritzen) wires, which produce a stable steel layer on the sliding surface of the cylinder liner. PTWA technology has become one of the most important alternatives to cast–iron cylinder liners. The process produces thin ferrous coatings with excellent adhesion, allowing smaller cylinder spacing, improved heat transfer, reduced engine mass, and lower friction losses. As a result, PTWA is now used in modern lightweight aluminium engine blocks [43–45].

HVOF is another thermal coating technique that utilizes a flame spray process to form wear–resistant surfaces. Compared with conventional flame spraying, HVOF produces coatings with lower porosity, higher particle velocity, and improved bonding strength. These characteristics result in excellent wear resistance under severe tribological conditions, making HVOF particularly suitable for highly loaded engine components operating under severe sliding and abrasive wear conditions [46–48].

Tribosil technology modifies the surface of aluminium alloy cylinders with a laser. First, the block is cast from a cost–effective Al–Si alloy via gravity casting. Then, the sliding surface is alloyed with silicon using a laser beam, which melts the surface and simultaneously introduces Si particles in powder form. This process locally enriches the surface with silicon, forming a hypereutectic Al–Si alloy and enhancing tribological performance. Laser alloying modifies only the surface layer of the aluminium alloy, producing rapid solidification and a refined microstructure with no effect on the bulk material. This localized treatment improves hardness and wear resistance while maintaining the low density and thermal conductivity of the aluminium substrate [49,50].

Rotaplasma is a technology that produces iron–based coatings through a plasma spray process.

In addition to cylinders, pistons in reciprocating IC engines and compressors are subjected to significant loads, making material fatigue a primary cause of damage. This fatigue arises from the reciprocating motion of the piston within the cylinder under variable operating conditions.

Pistons must maintain a precise fit with the cylinder and withstand the maximum pressure of the working medium. Key design requirements include dynamic durability, wear resistance, and an appropriate coefficient of thermal expansion. The piston bowl must also endure high temperatures and pressures.

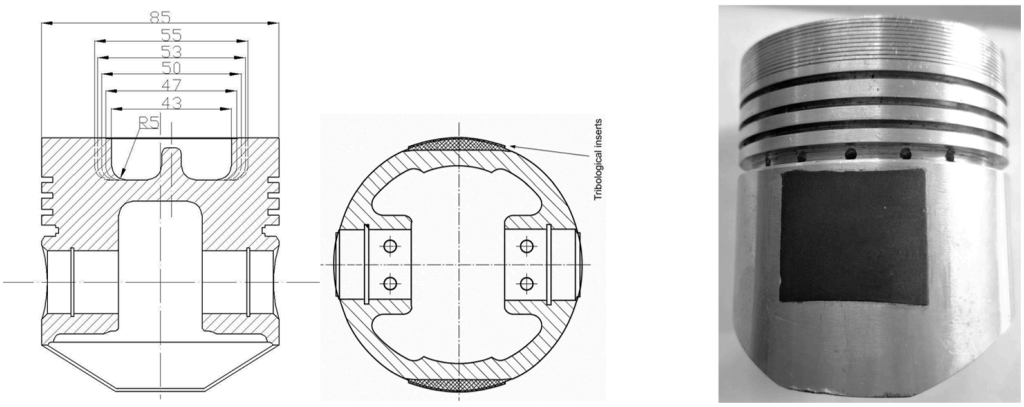
During reciprocating motion, the piston's supporting elements function as guides. Optimization of the piston's sliding components and the cylinder liner can be achieved through various methods aimed at reducing friction and wear.

Wear of steel sliding surfaces can be minimized using (MoS_2) as a solid lubricant. Micro–textures or reservoirs can be created on the piston bearing surfaces using a laser, similar to cylinder honing, allowing the solid lubricant to be embedded and enhancing tribological performance.

Manufacturers frequently use graphite and MoS_2 as solid lubricants and protective coatings on piston sliding surfaces. Graphite is the primary lubricant, while iron–alloy coatings are used for aluminium pistons. In some cases, the coating material is a composite of graphite, MoS_2, carbon fibers, and resin: graphite and MoS_2 reduce friction, carbon fibres improve wear resistance, and resin protects the surface, extending coating life.

An example of such optimization is the Monosteel piston for diesel engines in heavy–duty vehicles, designed to withstand maximum cylinder pressures of up to 25 MPa [51].

Figure 3 illustrates an original tribologically optimized aluminium alloy piston developed by researchers from the Faculty of Engineering, University of Kragujevac (FINK). Figure 3a presents a cross–sectional schematic view of the proposed piston design, while Figure 3b shows the manufactured experimental piston incorporating tribological inserts made of iron–based alloy or graphite. The proposed solution is intended for application in aluminium pistons used in internal combustion engines, as well as in reciprocating air compressors employed in the braking systems of trucks and buses. By introducing tribological inserts at the piston sliding surface, friction and wear between the piston and cylinder can be significantly reduced, leading to improved mechanical efficiency, lower fuel consumption, and extended service life. Furthermore, maintenance costs may be reduced because only the worn inserts need to be replaced instead of the complete piston assembly. The concept also demonstrates promising potential for future application in lightweight compressor systems for hybrid and electric vehicles [52,53].



(**a**) (**b**)

Figure 3. Optimized aluminium–alloy piston (FINK solution): (**a**) piston cross–section; (**b**) experimental piston with a tribological insert in the skirt area for engine DMB Lombardini/3LD450.

Experimental investigations of the engine on a test rig demonstrated a reduction in specific work of mechanical losses during operation with an aluminum piston equipped with tribological inserts compared with the conventional piston (Figure 4) [53].

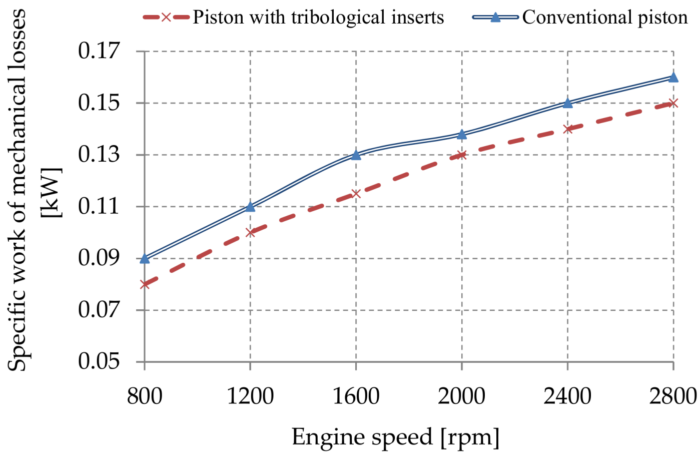


Figure 4. Contribution of an aluminum piston with tribological inserts to the reduction of specific mechanical losses as a function of engine speed compared with a conventional piston.

Similar results were obtained with the new piston design developed for Mack's 15,000 cm^3 IC engines. The design features a two–part bearing surface with a central relief, enabling a 7% reduction in piston weight. Compared with the original design, mechanical losses, and consequently friction losses, were reduced by 17% [54].

Overall, surface engineering technologies should be regarded as complementary to alloy design and composite reinforcement in improving the performance of Al–Si engine components. Technologies such as plasma spraying, PTWA, HVOF, electroplating, and laser alloying effectively compensate for the lower wear resistance of aluminium alloys, enabling the development of lightweight engine components with improved tribological performance, durability, thermal stability, and fuel efficiency. As a result, the combination of optimized alloy composition, appropriate reinforcement, and advanced surface engineering represents one of the most promising strategies for future Al–Si engine components.

2.3. Applications of Hypoeutectic Al–Si Alloys in IC Engines and Aerospace

The use of aluminium instead of cast iron for manufacturing IC engine blocks results in a weight reduction of 15–35 kg [55]. Another advantage of aluminium alloys is their high thermal conductivity approximately four times that of grey cast iron, which improves heat dissipation from internal combustion (IC) engines and enables higher power output. However, the maximum allowable temperature limits the application of aluminium alloys in IC engine components. Consequently, the use of aluminium engine blocks in passenger vehicles is typically restricted to maximum cylinder pressures of 15 MPa [55].

Hypoeutectic Al–Si alloys are widely used in aerospace, automotive, and electronics manufacturing, owing to their excellent casting properties, fatigue strength, and corrosion resistance [56,57].

Conventional cast hypoeutectic Al–Si alloys typically exhibit large α–Al grains and needle–shaped eutectic Si in their microstructure [58]. These alloys represent an important group characterized by a favorable combination of machinability, castability, thermal conductivity, and corrosion resistance. They generally contain 5–12% Si, with common examples including $AlSi_7Mg$ (A356), $AlSi_9Cu_3$ (A380), and $AlSi_{10}Mg$ (A357).

In small–displacement IC engines, particularly for motorcycles [59], hypoeutectic Al–Si alloys are employed for components such as engine blocks, cylinder heads, intake manifolds, pistons, valve assembly, and cylinder liners [57,60–63]. An example of such an application is shown in Figure 5.

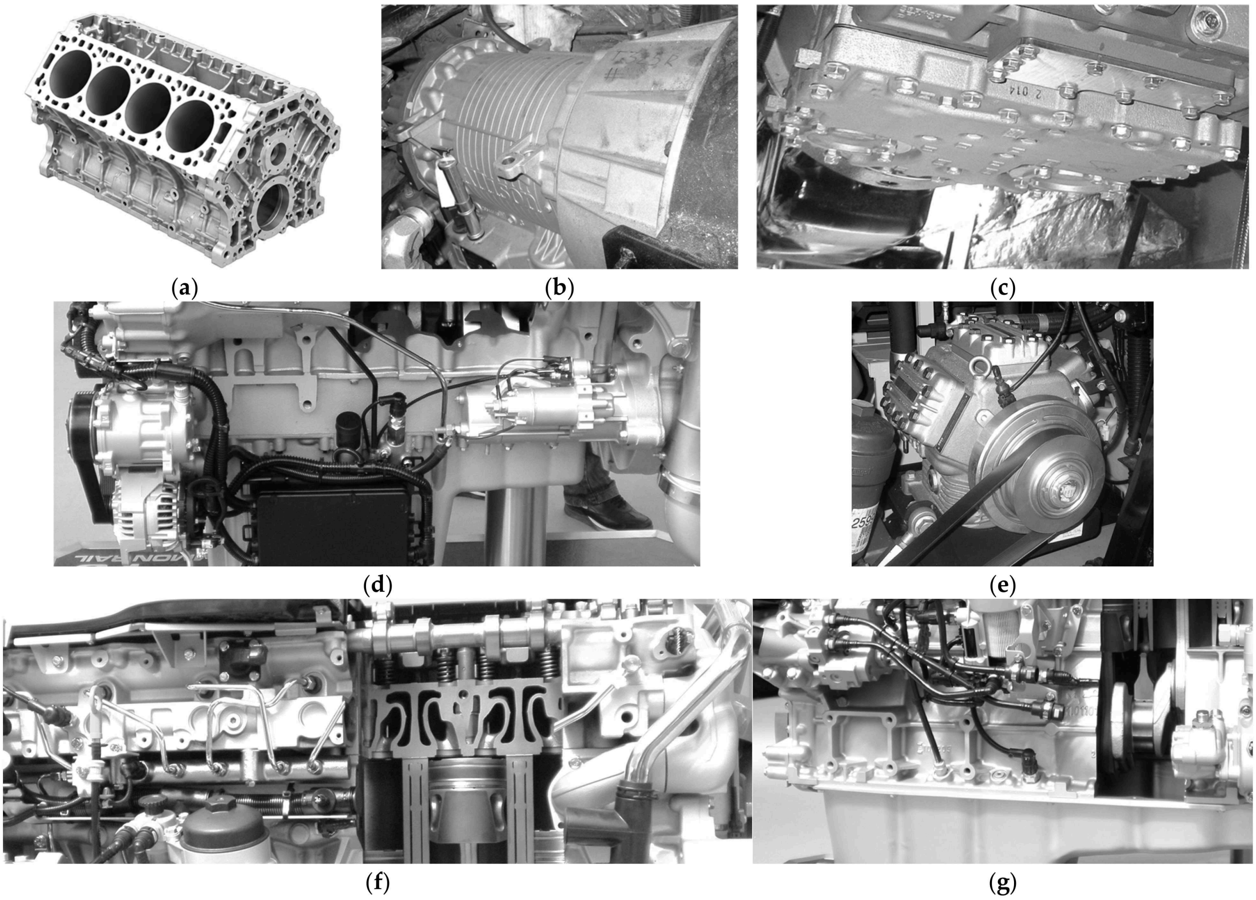


Figure 5. Photographs of Automotive Applications of Hypoeutectic Al–Si Alloys: (**a**) 3D model and cross–sectional view of a closed–deck V8 engine block made of A319 aluminium alloy; (**b**) A356 aluminum alloy housing of a six–speed automatic gearbox used in a city bus; (**c**) ADC12 aluminium alloy hydraulic valve body housing with internal channels and separator plate for an automatic gearbox; (**d**) A380 aluminium alloy alternator and starter motor housings mounted on a truck engine; (**e**) A356 aluminium alloy cylinder block of a reciprocating A/C compressor used in a city bus; (**f**) cross–section of the A356/A357 aluminium alloy cylinder head and cylinder of a six–cylinder truck engine; and (**g**) A380 aluminum alloy oil pan of a truck engine.

Figure 5a presents a 3D model of a closed–deck V8 engine block designed for casting using the heat–treatable A319 (Al–Si–Cu) aluminium alloy. The component has an approximate mass of 50 kg, which is significantly lower than the approximately 120 kg mass of comparable grey cast iron engine blocks. The replacement of cast iron with aluminium alloys in such applications represents a significant engineering challenge, as these materials must provide adequate mechanical performance and thermal fatigue resistance under elevated engine operating conditions [53,64].

A356 ($AlSi_7Mg_{0.3}$) and ADC12 ($AlSi_{11}Cu_3$) are hypoeutectic Al–Si casting alloys with different properties and applications. A356 provides higher strength, ductility, and corrosion resistance, making it suitable for structural automotive components such as transmission housings (Figure 5b), while ADC12 offers excellent castability and is widely used for high–pressure die–cast components such as gearbox housings, alternator housings, and pump housings; see Figure 5c [65].

Figure 5d presents an example of automotive applications of hypoeutectic Al–Si casting alloys, showing A380 ($AlSi_8Cu_3$) aluminium alloy alternator and starter motor housings mounted on a truck engine. A380 is an Al–Si–Cu alloy widely used in high–pressure die casting due to its excellent castability, dimensional stability, and good mechanical properties, making it suitable for complex automotive components such as housings, covers, and brackets.

Figure 5e–g illustrate the application of hypoeutectic Al–Si aluminium alloys in automotive components. Figure 5e shows an A356 aluminium alloy cylinder block of a reciprocating A/C compressor used in a city bus, while Figure 5f presents a cross–section of an A356/A357 aluminium alloy cylinder head and cylinder of a six–cylinder truck engine. Figure 5g shows an A380 aluminium alloy oil pan of a truck engine, demonstrating the use of these alloys in components requiring low weight, good castability, thermal performance, and adequate mechanical strength.

Aluminium casting alloys are widely used in internal combustion engine components, including cylinder heads and engine blocks, due to their low density, good thermal conductivity, and adequate mechanical properties. Continuous developments in casting technologies and microstructure control have further expanded their application in automotive structural and powertrain components.

Compared with the previously discussed aluminium casting alloys, $AlSi_9Cu_3$ (EN AC–46000) is a hypoeutectic Al–Si–Cu alloy that provides an excellent balance of castability, strength, and dimensional stability, making it suitable for complex automotive components produced by high–pressure die casting (HPDC). A typical application example is an aluminium engine block cast from AlSi9Cu3 alloy, incorporating six ingates and integrated vacuum channels that enable the production of complex geometries with reduced porosity and improved casting quality [66].

Al–Si alloys have been widely used in aerospace applications since the early development of aircraft due to their low density, good castability, and favorable mechanical properties, too. The continuous demand for weight reduction in aviation has promoted the development of lightweight aluminium alloys, and today these materials are also essential in automotive applications to improve fuel efficiency and reduce CO_2 emissions.

The modern aerospace industry employs investment casting to manufacture complex components while achieving significant reductions in weight and production cost. For example, the wing fitting of the Embraer Phenom aircraft is produced as a single F357 casting without welding. Other components, such as the rear frame electronics mount and the tail–rotor gearbox housing, are manufactured by precision sand casting using D357 alloy [67,68].

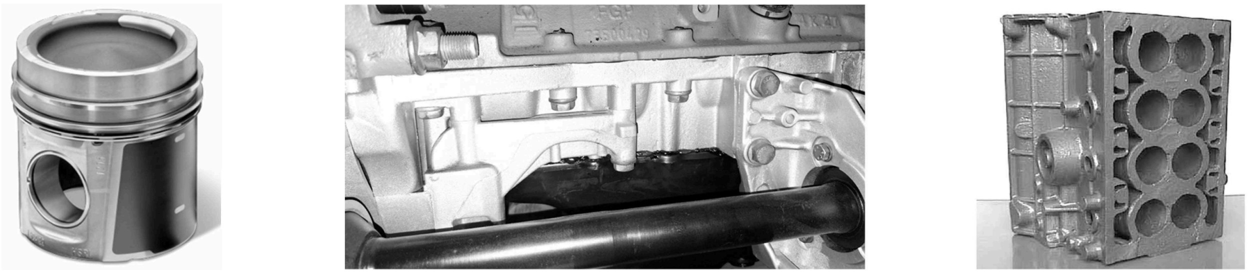
Hypoeutectic A357 ($AlSi_7Mg$) alloy is also used in the airframe structure and fuel tank of the Alcoa AGM–86 cruise missile. Approx. 80% of the missile structure is manufactured from Al–Si casting alloys, including the nose cone, inertial navigation compartment, engine air intake, wing components, mounting brackets, and large fuel tank castings. These components require high dimensional accuracy and complex geometries, demonstrating the versatility of Al–Si casting alloys in aerospace applications [67,68].

Despite their excellent castability and corrosion resistance, hypoeutectic Al–Si alloys generally exhibit lower wear resistance than hypereutectic alloys because of their lower volume fraction of hard silicon particles. Consequently, their application in heavily loaded tribological components often requires additional surface treatments or protective coatings to improve wear performance.

2.4. Applications of Eutectic Al–Si Alloys in Internal Combustion Engines

Eutectic Al–Si alloys, containing approx. 12.6 wt.% Si, represent an important subgroup of aluminium casting alloys. They are characterized by excellent castability, good wear resistance, and microstructural stability at elevated temperatures (e.g., 250–350 °C), making them widely used in the automotive, aerospace, and mechanical engineering industries [69].

Eutectic Al–Si alloys are widely employed in engine blocks of medium–displacement passenger vehicle engines because of their excellent castability and balanced mechanical properties (Figure 6). In contrast, hypereutectic alloys, such as $AlSi_{17}Cu_4Mg$ and 4032 ($AlSi_{12}CuMgNi$), are primarily used for highly wear–resistant engine components, including pistons and linerless cylinder bores, where their high silicon content provides superior wear resistance, low thermal expansion, and excellent dimensional stability under severe operating conditions. Figure 6 also shows a 4032 aluminium alloy engine piston with a coated piston skirt as a representative application of hypereutectic Al–Si alloys.



(**a**) (**b**) (**c**)

Figure 6. Applications of Eutectic and Hypereutectic Al–Si Alloys: (**a**) 4032 aluminium alloy piston with a coated piston skirt; (**b**) upper oil pan made of AlSi12 aluminium alloy; and (**c**) linerless engine block made from a hypereutectic Al–Si (Alusil–type) alloy for a VCR engine prototype.

Figure 6 illustrates typical applications of eutectic and hypereutectic Al–Si alloys in internal combustion engines. While eutectic alloys are commonly used for cast engine components such as oil pans, hypereutectic alloys are preferred for highly wear–resistant components, including pistons and linerless engine blocks [53,70,71].

Eutectic Al–Si alloys provide a balanced combination of castability, wear resistance, thermal conductivity, and low manufacturing cost. Consequently, they remain among the most widely used Al–Si casting alloys for passenger vehicle engine components.

2.5. Typical Applications of Hypereutectic Al–Si Alloys in Internal Combustion Engines

Al–Si alloys are increasingly used in the automotive industry due to their high thermal conductivity, which enables more efficient heat dissipation during engine operation compared with cast iron, as well as their high strength–to–weight ratio [59]. The continuous pursuit of higher efficiency and improved engine performance requires increased maximum operating temperatures and pressures within the engine.

Hypoeutectic Al–Si alloys may exhibit reduced strength at elevated temperatures and often require additional measures to improve their thermal stability. The use of linerless cylinder bores in internal combustion engines can improve engine efficiency by enhancing heat transfer and reducing component mass compared with hypoeutectic Al–Si engine blocks equipped with cast iron cylinder liners, which may not provide sufficient tribological performance under severe operating conditions.

An alternative approach is the use of hypereutectic Al–Si alloys for engine blocks or cylinder bores. At high Si contents (>12.6 wt.%), primary silicon precipitates form in the microstructure, increasing hardness and improving tribological performance. Achieving a uniform distribution and controlled size of primary Si particles is critical, as non–uniform microstructures may promote localized wear and contribute to premature engine failure [23].

One of the first commercial applications of hypereutectic Al–Si alloys in internal combustion engine components was the Chevrolet Vega engine block, introduced by General Motors (GM) in the 1970s. The IC engine block of this vehicle was manufactured from A390 hypereutectic Al–Si alloy (approx. 17 wt.% Si and 4–5 wt.% Cu), as shown in Figure 7 [72,73].

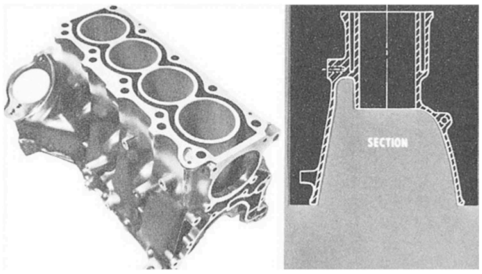


Figure 7. Chevrolet Vega Engine Block with Hypereutectic Al–Si (Alusil–Type) Cylinder Bores.

Engine blocks manufactured from hypereutectic Al–Si alloys have undergone significant development and are now produced under various trade names, including Alusil, Lokasil, Silitec, DiASil, Mercosil, and ALBOND. These technologies are used by manufacturers such as Mercedes–Benz, Audi, BMW, Volvo, Honda, and others. Some of these approaches have also been applied in marine engines (e.g., Mercosil). Alusil technology is based on the production of a monolithic IC engine block from the hypereutectic $AlSi_{17}Cu_4Mg$ alloy, in which primary silicon particles are distributed within the aluminium matrix. After machining and chemical etching/polishing, the exposed silicon particles form a wear–resistant cylinder surface and provide the required tribological properties for reliable engine operation. The Silitec process, applied by Mercedes–Benz, involves the application of silicon–rich layers to monoblock engines manufactured from hypereutectic Al–Si alloys. The Lokasil concept enables the formation of a locally optimized microstructure for severe operating conditions, improving wear resistance, thermal stability, and dimensional stability of the engine block. Composite cylinder liners are produced by infiltrating hollow cylindrical porous preforms containing ceramic fibres and silicon particles (Lokasil I) or silicon particles only (Lokasil II) with aluminium alloy during the casting process [53,74].

The selection of Al–Si alloys for internal combustion engine components depends strongly on their silicon content, microstructure, and required operating conditions. Hypoeutectic alloys provide a favorable balance between castability, mechanical properties, and corrosion resistance, making them suitable for engine blocks, cylinder heads, and structural components. Eutectic alloys are widely applied in cast automotive components due to their excellent castability, thermal conductivity, and cost–effectiveness. In contrast, hypereutectic Al–Si alloys are preferred for applications requiring high wear resistance and dimensional stability, such as pistons and linerless cylinder bores. The continuous development of technologies such as Alusil and Lokasil demonstrates the importance of controlling silicon morphology and distribution to achieve improved tribological performance and extended engine durability.

The A390 alloy, containing approximately 17 wt.% Si, 4–5 wt.% Cu, and 0.5 wt.% Mg, provides excellent wear resistance due to the presence of primary silicon particles. However, its relatively high Cu content reduces corrosion resistance, limiting its suitability for marine applications. Consequently, Cu–free hypereutectic Al–Si alloys, such as A391 (Mercosil), were developed for marine engine blocks, offering improved corrosion resistance while maintaining favorable tribological properties through a uniform distribution of primary Si particles. A modified A391 alloy containing Ni has also been investigated to improve machinability through the formation of Ni–containing intermetallic phases, such as $NiAl_3$ [75,76].

Today, hypereutectic Al–Si alloys are widely used for manufacturing IC engine blocks, cylinder liners, pistons, pumps, compressors, and other components where high wear resistance and dimensional stability are required. Selected examples of hypereutectic Al–Si alloy applications in IC engine components are presented in Figure 8 [20,55,71,76,77].

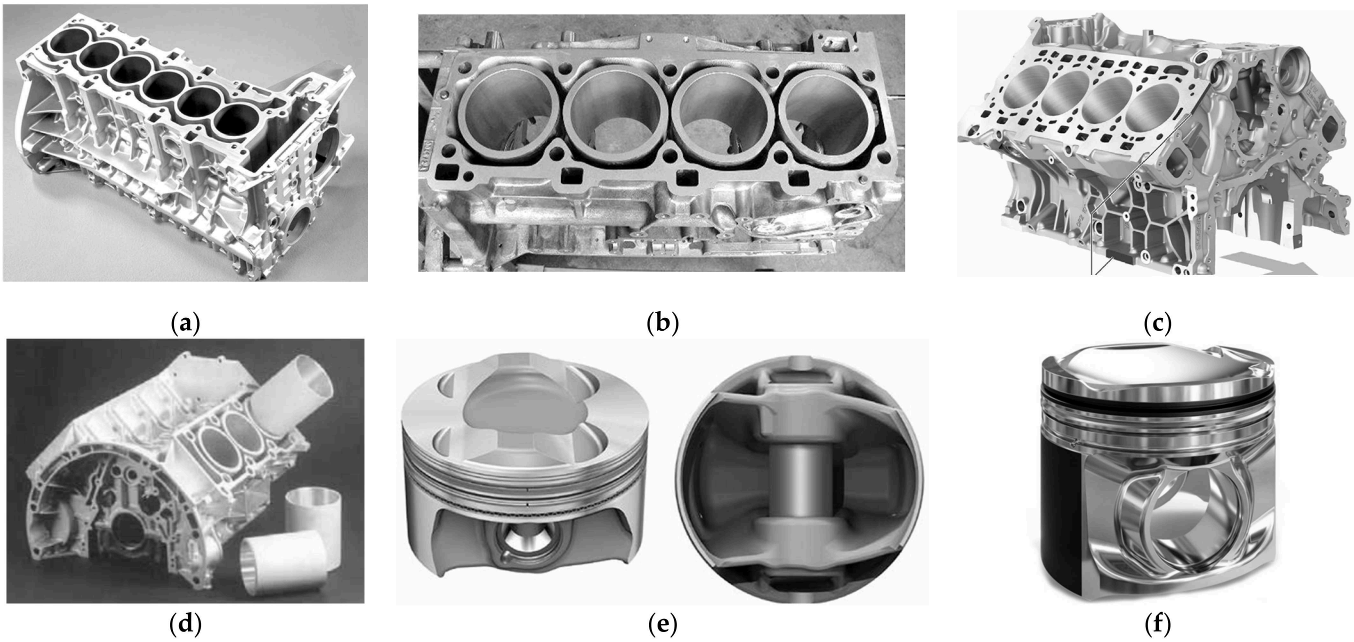


Figure 8. Applications of Hypereutectic Al–Si Alloys in Engine Parts: (**a**) BMW N52 open–deck engine block with Alusil–type hypereutectic Al–Si cylinder surfaces; (**b**) photograph of a Porsche 944/968 open–deck engine block with Alusil–type hypereutectic Al–Si cylinder bores; (**c**) Audi 4.0 L V8 TFSI (EA825) engine block manufactured from eutectic $AlSi_9Cu_3$ alloy with APS–coated cylinder bores; (**d**) DaimlerChrysler six–cylinder gasoline engine block with cast–in Silitec hypereutectic Al–Si liners for improved wear resistance; (**e**) Audi 4.0 L V8 TFSI (EA825) engine piston made of a 4032–type hypereutectic Al–Si alloy; (**f**) MAHLE high–silicon hypereutectic Al–Si piston alloy for heavy–duty diesel engine applications.

Figure 8a shows the BMW N52 inline six–cylinder engine, which represents a modern application of hypereutectic Al–Si technology. Its open–deck magnesium–aluminium composite crankcase incorporates Alusil–type cylinder surfaces, where primary silicon particles provide high wear resistance, reduced friction, and dimensional stability during engine operation. Unlike conventional cast iron cylinder liners, the Alusil structure enables a linerless cylinder design [23].

Figure 8b presents the Porsche 944/968 four–cylinder engine block as another example of Alusil technology. In this application, a hypereutectic Al–Si alloy provides wear–resistant cylinder surfaces without conventional cast iron liners. After machining, the exposed primary silicon particles form a durable tribological surface, contributing to improved wear resistance and dimensional stability during engine operation [23].

Figure 8c shows the Audi 4.0 L V8 TFSI (EA825) engine block, which represents an alternative approach to achieving wear–resistant cylinder surfaces. The closed–deck cylinder block is manufactured from eutectic $AlSi_9Cu_3$ aluminium alloy, while the cylinder bores are coated with a thin iron–based layer deposited by the APS process. To ensure sufficient adhesion and durability of the coating, the cylinder walls are first machined with a special tool that creates a dovetail–patterned surface. The resulting undercuts provide mechanical interlocking and improve the adhesion of the APS coating, enabling high wear resistance and reliable operation under severe engine conditions [78].

Figure 8d illustrates the DaimlerChrysler six–cylinder gasoline engine block equipped with Silitec liners. Silitec technology belongs to the group of high–silicon hypereutectic Al–Si cylinder liner materials, comparable to $Al_{20}Si$–$Al_{25}Si$ compositions. The high silicon content provides a wear–resistant cylinder surface through the presence of primary silicon particles, enabling lightweight aluminium engine blocks with improved tribological performance compared with conventional cast iron liners [74].

Figure 8e shows the piston application of hypereutectic Al–Si alloys in the Audi 4.0 L V8 TFSI (EA825) engine. High–performance engine pistons are typically manufactured from Al–Si–Cu–Mg–Ni alloys, such as $AlSi_{12}CuMgNi$ (4032–type), which provide low thermal expansion, high wear resistance, and excellent dimensional stability under high–temperature operating conditions [78].

Figure 8f presents a MAHLE high–silicon hypereutectic Al–Si piston alloy used for heavy–duty diesel engine applications. $Al_{20}Si$–type piston materials are characterized by a high fraction of silicon particles, which improves wear resistance, reduces thermal expansion, and enhances dimensional stability at elevated temperatures. These properties make them suitable for pistons subjected to high mechanical and thermal loads [79].

In addition to original factory engine components made from hypereutectic Al–Si alloys, aftermarket pistons are widely used in modified and high–performance engines where increased power output results in higher mechanical and thermal stresses. Examples of hypereutectic Al–Si alloy pistons manufactured by Speed–Pro and KB Performance are presented in Figures 9 and 10 [80,81].

(**a**) (**b**) (**c**) (**d**)

Figure 9. Examples of Speed–Pro hypereutectic Al–Si alloy pistons for high–performance automotive engines: (**a**) Ford Small Block 289/302 engine (9.0:1 compression ratio); (**b**) Chevrolet 350 Small Block V8 engine (H423DCP); (**c**) Chevrolet 454 Big Block V8 engine (H426CP); (**d**) Chevrolet 400 Small Block V8 engine (H400CP).

(**a**) (**b**) (**c**) (**d**)

Figure 10. Examples of KB Performance hypereutectic Al–Si alloy pistons for high–performance automotive engines: (**a**) KB115 flat–top piston for Ford 302 Small Block V8 engine (9.0:1 compression ratio); (**b**) KB138 D–cup piston for Ford 460 Big Block V8 engine; (**c**) KB116 piston for Chevrolet 327 Small Block V8 engine; (**d**) KB160 piston for Chevrolet 396/402 Big Block V8 engine.

https://doi.org/10.3390/lubricants14070277

The Speed–Pro hypereutectic Al–Si alloy pistons shown in Figure 9 represent typical aftermarket applications in high–performance Ford and Chevrolet V8 engines. These pistons are designed for increased mechanical and thermal loading conditions associated with modified engines and higher power outputs. The high silicon content of the alloy reduces thermal expansion and improves wear resistance, enabling stable operation under elevated temperatures and combustion pressures [80].

Similar applications of hypereutectic Al–Si alloy pistons are shown in Figure 10 for KB Performance Pistons. The KB115, KB138, KB116, and KB160 piston models demonstrate the use of high–silicon aluminium alloys in various Ford and Chevrolet Small Block and Big Block V8 engines. The combination of low thermal expansion, high hardness, and improved dimensional stability makes these materials suitable for performance engines operating under increased thermal and mechanical stresses [81].

These examples demonstrate that hypereutectic Al–Si alloys are widely applied not only in original equipment engine components but also in aftermarket performance applications where improved wear resistance and thermal stability are required.

3. Future Research Directions

Future development of Al–Si alloys for internal combustion engines will primarily focus on improving wear resistance, thermal stability, and sustainability. Particular attention should be directed toward the optimization of primary Si morphology in hypereutectic alloys, development of linerless engine blocks, and implementation of environmentally friendly surface engineering technologies. Furthermore, hybrid approaches involving laser alloying, thermal spraying, and nano–reinforcements such as graphene, carbon nanotubes, SiC, and Al_2O_3 nanoparticles are expected to play an important role in the next generation of lightweight engine components. The application of artificial intelligence and machine learning for alloy design and performance prediction also represents a promising research direction.

Besides the continuous development of Al–Si alloys with improved mechanical and tribological properties, future research should increasingly address sustainability requirements and circular economy principles in the automotive and mechanical engineering sectors. In this regard, aluminum represents one of the most important engineering materials due to its unique combination of low density, favorable strength–to–weight ratio, corrosion resistance, and excellent recyclability. Unlike many conventional metallic materials, aluminum can be repeatedly recycled and returned to production cycles with only minor losses in material quality, thereby significantly reducing raw material consumption, energy demand, and environmental impact.

The importance of aluminum recycling extends beyond environmental considerations and directly influences the economic sustainability of modern manufacturing systems. According to data from literature [82], aluminum plays a central role in circular economy strategies because recycled aluminum requires only a fraction of the energy needed for primary aluminum production while maintaining properties suitable for demanding engineering applications. Consequently, the increased utilization of recycled aluminum alloys in vehicle structures, engine components, and compressor systems represents an important pathway toward reducing the overall carbon footprint of transportation technologies.

From the perspective of internal combustion engines and reciprocating compressors, future investigations should focus on the optimization of recycling routes for Al–Si alloys used in pistons, cylinder liners, cylinder blocks, and other tribologically loaded components. Since pistons constitute one of the most widespread aluminum components in powertrain systems, their recovery, remanufacturing, and reuse offer significant opportunities for material savings and resource conservation. Furthermore, the development of advanced recycling technologies capable of preserving alloy composition, microstructural stability, and tribological performance will become increasingly important as sustainability requirements continue to grow.

At the same time, the benefits of lightweight aluminum components can be further enhanced through the implementation of advanced tribological solutions. Although significant improvements have been achieved through optimized piston geometries, surface treatments, coatings, and tribological inserts, friction and wear remain major sources of energy loss in piston–cylinder assemblies. Therefore, future research should investigate the combined effects of recycled Al–Si alloys, surface engineering technologies, and advanced lubrication systems on the overall efficiency and durability of engines and compressors.

Particular attention should be devoted to lubricants containing carbon nanotube (CNT) additives. Recent studies have demonstrated that CNT–enhanced lubricants can reduce friction and wear, improve load–carrying capacity, promote the formation of protective tribofilms, and enhance heat dissipation under severe operating conditions. These characteristics are particularly relevant for piston engines, reciprocating compressors, and their transmission mechanisms, where tribological losses directly affect fuel consumption, energy efficiency, operating temperatures, and component lifetime.

Recent findings reported by Bukvić et al. showed that carbon nanotube additives positively influence the efficiency and vibration characteristics of worm gear transmissions. These results indicate that nano–enhanced lubrication technologies may provide substantial benefits in a broader range of tribological systems, including piston–cylinder contacts and compressor mechanisms. Consequently, future research should focus on evaluating the synergistic effects of tribologically optimized aluminum–alloy components, tribological inserts, and CNT–based lubricants under realistic operating conditions [83].

Such an integrated approach, combining recyclable Al–Si alloys, advanced surface engineering, and nano–enhanced lubrication technologies, could contribute to the development of the next generation of lightweight, energy–efficient, and environmentally sustainable propulsion and compressor systems. This research direction is expected to remain important for hybrid powertrains, advanced internal combustion engines, and reciprocating compressor systems, where lightweight construction, reduced energy losses, high reliability, and sustainable material utilization remain key design objectives.

Another important future research direction is the application of advanced manufacturing technologies, including additive manufacturing (AM), for the production of Al–Si alloy components with tailored microstructures. Additive manufacturing enables precise control of cooling rates, solidification behavior, and silicon particle distribution, which may provide new possibilities for optimizing the wear resistance and mechanical performance of hypereutectic Al–Si alloys. Further investigations are required to overcome current challenges related to porosity, anisotropy, surface quality, and large–scale industrial implementation of additively manufactured engine components [84,85].

Future alloy development should also focus on controlling the size, morphology, and spatial distribution of primary silicon particles in hypereutectic Al–Si alloys. Excessive silicon particle size or non–uniform distribution can negatively affect fatigue resistance and wear behavior, while refined and uniformly distributed primary Si particles can provide improved tribological performance. Advanced solidification control techniques, inoculation methods, and thermomechanical processing routes represent promising approaches for achieving optimized microstructures for highly loaded engine and compressor components [86].

4. Conclusions

i. Al–Si alloys are essential materials in modern internal combustion engines due to their low density, high thermal conductivity, corrosion resistance, and good castability, enabling weight reduction, improved fuel efficiency, and effective thermal management.
ii. Hypoeutectic Al–Si alloys remain widely used for engine components such as cylinder blocks, cylinder heads, and pistons, where good castability, machinability, and corrosion resistance are required.
iii. Eutectic Al–Si alloys provide a balanced combination of mechanical properties, wear resistance, and thermal stability, making them suitable for highly loaded engine components, including cylinder blocks and thermally exposed parts.
iv. Hypereutectic Al–Si alloys provide superior hardness, wear resistance, and tribological performance due to the presence of primary silicon particles and are successfully applied in linerless engine blocks, cylinder liners, pistons, and other high–load components using technologies such as Alusil, Lokasil, Silitec, and Mercosil.
v. Surface engineering approaches, including atmospheric plasma spraying, electroplating, laser–based surface modification, and solid lubricant technologies, significantly enhance the tribological performance and service life of Al–Si engine components.
vi. The application of Al–Si alloys contributes to improved engine efficiency, increased operating temperatures and pressures, and reduced component mass, supporting the development of more efficient and environmentally compliant powertrain systems.
vii. Automotive and other demanding engineering applications demonstrate the versatility of Al–Si alloys in achieving lightweight design combined with adequate mechanical performance, reliability, and durability.
viii. Advanced tribological solutions, including aluminium pistons with tribological inserts and optimized surface treatments, provide additional opportunities for reducing friction and wear in piston–cylinder assemblies and extending component lifetime.
ix. The high recyclability of aluminium and the implementation of circular economy principles represent important advantages of Al–Si alloys, as recycled aluminium can significantly reduce energy consumption and raw material requirements while maintaining suitable engineering properties.
x. Future developments will focus on integrating recycled Al–Si alloys with advanced surface engineering technologies, optimized microstructures, and nano–enhanced lubrication systems, including CNT–based lubricants, to further reduce friction losses and improve component efficiency.
xi. The combination of optimized alloy design, advanced tribological solutions, and sustainable manufacturing approaches offers significant potential for next–generation lightweight and energy–efficient internal combustion engines, hybrid powertrains, and reciprocating compressor systems.
xii. Overall, Al–Si alloys remain a key material system for improving engine performance, reducing energy losses, and minimizing environmental impact in conventional and advanced powertrain applications.
xiii. The tribological behavior of Al–Si alloys is strongly influenced by their microstructure, particularly the size, morphology, and distribution of silicon phases. In hypereutectic alloys, controlled refinement and uniform distribution of primary silicon particles are essential for achieving improved wear resistance, reduced friction, and long–term dimensional stability of highly loaded engine components.
xiv. The development of Al–Si alloy engine components demonstrates a continuous transition from conventional cast designs toward advanced linerless cylinder systems, surface–engineered solutions, and high–performance aftermarket applications. Technologies such as Alusil, Lokasil, Silitec, Mercosil, and APS–coated cylinder surfaces

provide different approaches for achieving the required balance between lightweight construction, wear resistance, and reliable operation under severe engine conditions.

xv. Future implementation of Al–Si alloys requires an integrated approach combining alloy design, microstructural optimization, recycling strategies, advanced surface engineering, and improved lubrication technologies. The synergy between these approaches provides significant potential for the development of lightweight, energy–efficient, and environmentally sustainable components for internal combustion engines, hybrid powertrains, and reciprocating compressor systems.

xvi. Overall, Al–Si alloys remain a key material system for advanced engine and compressor components due to their unique combination of low density, thermal conductivity, wear resistance, and recyclability. Continued progress in alloy development, tribological optimization, and sustainable manufacturing will determine their future role in lightweight and energy–efficient powertrain technologies.

Author Contributions: Conceptualization, B.S. and S.M. (Saša Milojević); methodology, S.M. (Saša Milojević) and S.M. (Slavica Miladinović); validation, S.G., S.M. (Saša Milojević) and S.M. (Slavica Miladinović); formal analysis, S.Č., S.M. (Saša Milojević) and S.M. (Slavica Miladinović); investigation, S.Č., S.M. (Saša Milojević) and S.M. (Slavica Miladinović); resources, S.Č., S.M. (Saša Milojević) and S.M. (Slavica Miladinović); data curation, S.G. and S.M. (Slavica Miladinović); writing—original draft preparation, S.Č., S.M. (Saša Milojević) and S.M. (Slavica Miladinović); writing—review and editing, B.S. and S.G.; visualization, S.M. (Saša Milojević); supervision, B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been performed as a part of activities within the projects 451–03–33/2026–03/200107 and 451–03–34/2026–03/200107, supported by the Republic of Serbia, Ministry of Science, Technological Development and Innovation.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Kahn Ribeiro, S.; Kobayashi, S.; Beuthe, M.; Gasca, J.; Greene, D.; Lee, D.S.; Muromachi, Y.; Newton, P.J.; Plotkin, S.; Sperling, D.; et al. Transport and Its Infrastructure. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press Cambridge: Cambridge, UK; New York, NY, USA, 2007; pp. 323–385.
2. Wang, L.; Di, C.; Liu, Q.; Song, L.; Jiao, F. Energy Saving and Emission Reduction of Study on Lightening of Dump Truck Carriage. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *512*, 012003. [CrossRef]
3. Joost, W.J. Reducing Vehicle Weight and Improving U.S. Energy Efficiency Using Integrated Computational Materials Engineering. *JOM* **2012**, *64*, 1032–1038. [CrossRef]
4. Bangde, S.; Kini, C.; Pai, A. Reconfigurable Body Exterior Panels: A Review. *J. Mech. Eng. Res. Dev.* **2020**, *43*, 14–23.
5. Hirsch, J. Aluminium in Innovative Light–Weight Car Design. *Mater. Trans.* **2011**, *52*, 818–824. [CrossRef]
6. Dudek, P.; Zagórski, K. Cost, Resources, and Energy Efficiency of Additive Manufacturing. *E3S Web Conf.* **2017**, *14*, 01040. [CrossRef]
7. Chirinda, G.; Matope, S. *The Lighter the Better: Weight Reduction in the Automotive Industry and Its Impact on Fuel Consumption and Climate Change*; IEOM Society International: Southfield, MI, USA, 2020; p. 533.
8. Liu, J.; Zhang, Y.; Liao, B. A Review on Preparation Process and Tribological Performance of Coatings for Internal Combustion Engine Piston Ring. *Adv. Mech. Eng.* **2023**, *15*, 168781322311757. [CrossRef]
9. Davis, J.R. Aluminum and Aluminum Alloys. In *Alloying: Understanding the Basics*; ASM International: New York, NY, USA, 2001; pp. 351–416.
10. Google Scholar. Available online: https://scholar.google.com (accessed on 15 May 2026).
11. Salonitis, K.; Jolly, M.; Pagone, E.; Papanikolaou, M. Life–Cycle and Energy Assessment of Automotive Component Manufacturing: The Dilemma Between Aluminum and Cast Iron. *Energies* **2019**, *12*, 2557. [CrossRef]

12. Modaresi, R.; Pauliuk, S.; Løvik, A.N.; Müller, D.B. Global Carbon Benefits of Material Substitution in Passenger Cars Until 2050 and the Impact on the Steel and Aluminum Industries. *Environ. Sci. Technol.* **2014**, *48*, 10776–10784. [CrossRef] [PubMed]
13. Zhou, X.; Jiang, J.; Hu, Z.; Hua, L. Lightweight Materials in Electric Vehicles. *Int. J. Automot. Manuf. Mater.* **2022**, *1*, 3. [CrossRef]
14. Baek, S.; Park, S. Thermal Analysis of a Battery Cooling System with Aluminum Cooling Plates for Hybrid Electric Vehicles and Electric Vehicles. *Trans. Korean Soc. Automot. Eng.* **2014**, *22*, 60–67. [CrossRef]
15. Baumeister, J.; Weise, J.; Hirtz, E.; Höhne, K.; Hohe, J. Applications of Aluminium Hybrid Foam Sandwiches in Battery Housings for Electric Vehicles: Anwendung von Aluminium-Hybridschaum-Sandwichen in Batteriegehäusen von Elektrofahrzeugen. *Mater. Werkst.* **2014**, *45*, 1099–1107. [CrossRef]
16. Behi, H.; Karimi, D.; Kalogiannis, T.; Van Mierlo, J.; Berecibar, M. New Concept of Hybrid Cooling System for Fast Charging of Electric Vehicles. *J. Energy Storage* **2024**, *97*, 112994. [CrossRef]
17. Naresh, G.; Praveenkumar, T.; Madheswaran, D.K.; Solomon, J.M.; Goud Kureli, S.; Kolhe, Y.K.; Lalvani, J.I.J.R. Advancing Structural Efficacy and Resonance Performance of Battery Enclosures through Multi–Objective Optimization. *J. Low Freq. Noise Vib. Act. Control* **2024**, *43*, 1895–1909. [CrossRef]
18. Singh, R. Lightweight Metals and Alloys in Electric Vehicle Manufacturing: Enhancing Performance and Efficiency. *Int. J. Sci. Res. Arch.* **2024**, *13*, 1735–1742. [CrossRef]
19. Yay, İ.; Demirci, E.; Özcan, A.R. Multi–Objective Optimization of Aluminum Foam–Filled Battery Boxes for Electric Vehicle Safety. *Lat. Am. J. Solids Struct.* **2025**, *22*, e8408. [CrossRef]
20. Jorstad, J.; Apelian, D. Hypereutectic Al–Si Alloys: Practical Casting Considerations. *Int. J. Met.* **2009**, *3*, 13–36. [CrossRef]
21. Mbuya, T.O.; Odera, B.O.; Ng'ang'a, S.P. Influence of Iron on Castability and Properties of Aluminium Silicon Alloys: Literature Review. *Int. J. Cast Met. Res.* **2003**, *16*, 451–465. [CrossRef]
22. Ikhmayies, S. Phase Diagrams of Al–Si System: Methods and Protocols. In *Energy Technology 2019: Carbon Dioxide Management and Other Technologies*; Springer International Publishing: Cham, Switzerland, 2019; pp. 231–237.
23. Miladinović, S.; Stojanović, B.; Gajević, S.; Vencl, A. Hypereutectic Aluminum Alloys and Composites: A Review. *Silicon* **2023**, *15*, 2507–2527. [CrossRef]
24. Hatch, J.E. *Aluminium Propertiesand Physical Metallurgy*; American Society for Metals: Ohio, CO, USA, 1984.
25. Campbell, J. Chapter 16—-Casting. In *Complete Casting Handbook*, 2nd ed.; Campbell, J., Ed.; Butterworth–Heinemann: Boston, MA, USA, 2015; pp. 821–882.
26. Mostafa, A.; Alshabatat, N. Microstructural, Mechanical and Wear Properties of Al–1.3%Si Alloy as Compared to Hypo/Hyper–Eutectic Compositions in Al–Si Alloy System. *Crystals* **2022**, *12*, 719. [CrossRef]
27. Ejiofor, J.U.; Reddy, R.G. Developments in the Processing and Properties of Particulate Al–Si Composites. *JOM* **1997**, *49*, 31–37. [CrossRef]
28. Ho, C.R.; Cantor, B. Modification of Hypoeutectic Al–Si Alloys. *J. Mater. Sci.* **1995**, *30*, 1912–1920. [CrossRef]
29. Zellele, D.M.; Yar–Mukhamedova, G.S.; Rutkowska–Gorczyca, M. A Review on Properties of Electrodeposited Nickel Composite Coatings: Ni–Al_2O_3, Ni–SiC, Ni–ZrO_2, Ni–TiO_2 and Ni–WC. *Materials* **2024**, *17*, 5715. [CrossRef]
30. Yan, Y.; Lu, L.; Huo, Y. Dry Sliding Tribological Behaviors of Electrodeposited Ni–GO/SiC Composite Coating on the 2218 Aluminum Alloy. *Materials* **2022**, *15*, 2834. [CrossRef] [PubMed]
31. Eskandari, A.; Gupta, M.; Joshi, S. Hybrid Thermal Spray: A Pathway to Realize Novel Coating Microstructures and Properties. *J. Therm. Spray Technol.* **2025**, *34*, 1517–1544. [CrossRef]
32. Vencl, A. Tribology of the Al–Si Alloy Based MMCs and Their Application in Automotive Industry. In *Engineered Metal Matrix Composites: Forming Methods, Material Properties and Industrial Applications*; Magagnin, L., Ed.; Nova Science Publishers: Long Island, NY, USA, 2012; pp. 127–166.
33. Boulos, M.I.; Fauchais, P.L.; Henne, R.H.; Pfender, E. Plasma in the Thermal Spray Coating Industry. In *Handbook of Thermal Plasmas*; Boulos, M.I., Fauchais, P.L., Pfender, E., Eds.; Springer International Publishing: Cham, Switzerland, 2023; pp. 1423–1508.
34. Stojanović, B.; Milojević, S. Chapter 2. Characterization, Manufacturing and Application of Metal Matrix Composites. In *Advances in Materials Science Research*; Wythers, M.C., Ed.; Nova Science Publishers, Inc.: New York, NY, USA, 2017; Volume 30, pp. 83–133.
35. Milojević, S.; Savić, S.; Mitrović, S.; Maric, D.; Krstić, B.; Stojanović, B.; Popović, V. Solving the Problem of Friction and Wear in Auxiliary Devices of Internal Combustion Engines on the Example of Reciprocating Air Compressor for Vehicles. *Teh. Vjesn.–Tech. Gaz.* **2023**, *30*, 122–130. [CrossRef]
36. Milojević, S.; Savić, S.; Maric, D.; Stopka, O.; Krstić, B.; Stojanovic, B. Correlation between Emission and Combustion Characteristics with the Compression Ratio and Fuel Injection Timing in Tribologically Optimized Diesel Engine. *Teh. Vjesn.* **2022**, *29*, 1210–1219. [CrossRef]
37. Milojević, S.; Glišović, J.; Savić, S.; Bošković, G.; Bukvić, M.; Stojanović, B. Particulate Matter Emission and Air Pollution Reduction by Applying Variable Systems in Tribologically Optimized Diesel Engines for Vehicles in Road Traffic. *Atmosphere* **2024**, *15*, 184. [CrossRef]

38. Martins, M.A.R.; Pinho, S.P.; Coutinho, J.A.P. Insights into the Nature of Eutectic and Deep Eutectic Mixtures. *J. Solut. Chem.* **2019**, *48*, 962–982. [CrossRef]
39. Betz, J. Werkstoffe im Dieselmotor und ihre Auswahl. In *Handbuch Dieselmotoren*; Tschöke, H., Mollenhauer, K., Maier, R., Eds.; Springer Fachmedien Wiesbaden: Wiesbaden, Germany, 2016; pp. 1–28.
40. Garcia, I.; Fransaer, J.; Celis, J.-P. Electrodeposition and Sliding Wear Resistance of Nickel Composite Coatings Containing Micron and Submicron SiC Particles. *Surf. Coat. Technol.* **2001**, *148*, 171–178. [CrossRef]
41. Schlesinger, M.; Paunovic, M. (Eds.) *Modern Electroplating*, 1st ed.; Wiley: Hoboken, NJ, USA, 2010.
42. MAHLE Aftermarket GmbH. *All About the Cylinder–Technical Information*; MAHLE Aftermarket GmbH: Stuttgart, Germany, 2021; p. 64.
43. Villafuerte, J. Plasma Transferred Wire Arc Process Fortifies Aluminum Engine Blocks. *AMP Tech. Artic.* **2014**, *172*, 37–38. [CrossRef]
44. Bobzin, K.; Ernst, F.; Zwick, J.; Schlaefer, T.; Cook, D.; Nassenstein, K.; Schwenk, A.; Schreiber, F.; Wenz, T.; Flores, G.; et al. Coating Bores of Light Metal Engine Blocks with a Nanocomposite Material Using the Plasma Transferred Wire Arc Thermal Spray Process. *J. Therm. Spray Technol.* **2008**, *17*, 344–351. [CrossRef]
45. O'Neil, N.; Kabir, A.S. Pulsed Waterjet Roughening of Cast Iron and Aluminum Alloy for Automotive Engine Remanufacturing with Plasma Transferred Wire Arc Coating. *Coatings* **2020**, *10*, 864. [CrossRef]
46. Gildersleeve, E.J.; Vaßen, R. Thermally Sprayed Functional Coatings and Multilayers: A Selection of Historical Applications and Potential Pathways for Future Innovation. *J. Therm. Spray Technol.* **2023**, *32*, 778–817. [CrossRef] [PubMed]
47. Davis, J.R. (Ed.) *Handbook of Thermal Spray Technology*; ASTM International: Geneva, Switzerland, 2004.
48. Pawlowski, L. *The Science and Engineering of Thermal Spray Coatings*; J. Wiley and Sons: Chichester, UK, 2008.
49. European Aluminium. *Applications—Power Train—Cylinder Linings*; European Aluminium: Brussels, Belgium, 2022.
50. Aubanel, L. Étude du Comportement Tribologique en Régime Lubrifié de Revêtements Cold Spray Composites à Base D'acier. Doctorat ès Sciences et Génie des Matériaux. Ph.D. Thesis, Université Paris Sciences et Lettres, Paris, France, 2022.
51. Yin, B.; Wang, X.; Xu, B.; Huang, G.; Kuang, X. Adaptability of Piston Skirt Coatings on the Tribological Performance of Heavy–Duty Diesel Engine under Low Viscosity Lubricant. *Ind. Lubr. Tribol.* **2021**, *73*, 986–992. [CrossRef]
52. Milojević, S.; Pešić, R.; Taranović, D. Tribological Principles of Constructing the Reciprocating Machines. *Tribol. Ind.* **2015**, *37*, 13–19.
53. Milojević, S.; Pešić, R.; Taranović, D.; Davinić, A. Tribological Optimization of Reciprocating Machines according to improving Performance. *Mobil. Veh. Mech. (MVM)* **2016**, *42*, 29–44.
54. Esser, J.; Gladwin, R.; Schneider, N.; Stumpf, W. Contribution fuel consumption reduction by optimizing pistons/piston rings. In *Internationaler Motorenkongress 2014*; Liebl, J., Ed.; Proceedings; Springer Fachmedien Wiesbaden: Wiesbaden, Germany, 2014; pp. 307–325.
55. Javidani, M.; Larouche, D. Application of Cast Al–Si Alloys in Internal Combustion Engine Components. *Int. Mater. Rev.* **2014**, *59*, 132–158. [CrossRef]
56. Liu, Y.; Xiong, S. Research Progress on Thermal Conductivity of High–Pressure Die–Cast Aluminum Alloys. *Metals* **2024**, *14*, 370. [CrossRef]
57. Huang, C.; Liu, Z.; Li, J. Influence of Alloying Element Mg on Na and Sr Modifying Al–7Si Hypoeutectic Alloy. *Materials* **2022**, *15*, 1537. [CrossRef] [PubMed]
58. Manani, S.; Pradhan, A.K. Effects of Melt Thermal Treatment on Cast Al–Si Alloys: A Review. *Mater. Today Proc.* **2022**, *62*, 6568–6572. [CrossRef]
59. Razin, A.A.; Ahammed, D.S.-S.; Khan, A.A.; Kaiser, M.S. Thermophysical Properties of Hypoeutectic, Eutectic and Hypereutectic Al–Si Automotive Alloys under Ageing Treatment. *J. Chem. Technol. Metall.* **2024**, *59*, 673–682. [CrossRef]
60. Zhang, A.; Li, Y. Thermal Conductivity of Aluminum Alloys—A Review. *Materials* **2023**, *16*, 2972. [CrossRef] [PubMed]
61. Machado, P.A.B.; Do Vale Quaresma, J.M.; Garcia, A.; Dos Santos, C.A. Investigation on Machinability in Turning of As–Cast and T6 Heat–Treated Al–(3, 7, 12%)Si–0.6%Mg Alloys. *J. Manuf. Process.* **2022**, *75*, 514–526. [CrossRef]
62. Timelli, G.; Fabrizi, A.; Vezzù, S.; De Mori, A. Design of Wear–Resistant Diecast AlSi9Cu3(Fe) Alloys for High–Temperature Components. *Metals* **2019**, *10*, 55. [CrossRef]
63. Vuksanovic, D.; Asanovic, V.; Scepanovic, J.; Radonjic, D. Effect of Chemical Composition and T6 Heat Treatment on the Mechanical Properties and Fracture Behaviour of Al–Si Alloys for IC Engine Components. *J. Min. Metall. Sect. B Metall.* **2021**, *57*, 195–207. [CrossRef]
64. Subhani, T.; Ramadan, M.; Fathy, N.; Khaliq, A.; Halim, K.S.A. Innovation in Metal Casting Processes: A Review of Metal Matrix Nanocomposites in Metal and Bimetal Castings. *Crystals* **2025**, *15*, 191. [CrossRef]
65. Lakshmikanthan, A.; Angadi, S.; Malik, V.; Saxena, K.K.; Prakash, C.; Dixit, S.; Mohammed, K.A. Mechanical and Tribological Properties of Aluminum–Based Metal–Matrix Composites. *Materials* **2022**, *15*, 6111. [CrossRef]

66. Grosselle, F.; Timelli, G.; Bonollo, F.; Molina, R. Correlation Between Microstructure and Mechanical Properties of Al–Si Diecast Engine Blocks. *Metall. Sci. Technol.* **2009**, *27*, 2–10.
67. Li, S.; Yue, X.; Li, Q.; Peng, H.; Dong, B.; Liu, T.; Yang, H.; Fan, J.; Shu, S.; Qiu, F.; et al. Development and Applications of Aluminum Alloys for Aerospace Industry. *J. Mater. Res. Technol.* **2023**, *27*, 944–983. [CrossRef]
68. Robles Hernandez, F.C.; Herrera Ramírez, J.M.; Mackay, R. Applications in the Automotive and Aerospace Industries. In *Al–Si Alloys*; Springer International Publishing: Cham, Switzerland, 2017; pp. 163–171.
69. Jin, L.; Liu, K.; Chen, X.-G. Improved Elevated Temperature Properties in Al–13%Si Piston Alloys by Mo Addition. *J. Mater. Eng. Perform.* **2020**, *29*, 126–134. [CrossRef]
70. Xue, G. Tribological Studies of Eutectic Al–Si Alloys Used for Automotive Engine Blocks Subjected to Sliding Wear Damage. Master Thesis, University of Windsor, Windsor, ON, Canada, 2009.
71. Donahue, R.; Fabiyi, P. Manufacturing Feasibility of All–Aluminum Automotive Engines Via Application of High Silicon Aluminum Alloy. In Proceedings of the SAE 2000 World Congress, Detroit, MI, USA, 6 March 2000. [CrossRef]
72. Jorstad, J.L. The hypereutectic aluminum−silicon alloy used to cast the Vega engine block. *Mod. Cast.* **1971**, *60*, 59−64.
73. Kneisler, F.J.; Martens, D.A.; Midgley, R.W. The Vega 2300 Engine. *SAE Trans.* **1971**, *80*, 520–545. [CrossRef]
74. Fuchs, H.; Wappelhorst, M. Leichtmetallwerkstoffe für hochbelastete Motorblöcke und Zylinderköpfe. *MTZ Mot. Z.* **2003**, *64*, 868–875. [CrossRef]
75. Dienwiebel, M.; Pöhlmann, K.; Scherge, M. Origins of the wear resistance of AlSi cylinder bore surfaces studies by surface analytical tools. *Tribol. Int.* **2007**, *40*, 1597–1602. [CrossRef]
76. Tupaj, M.; Orłowicz, A.W.; Mróz, M.; Trytek, A.; Dolata, A.J.; Dziedzic, A. A Study on Material Properties of Intermetallic Phases in a Multicomponent Hypereutectic Al–Si Alloy with the Use of Nanoindentation Testing. *Materials* **2020**, *13*, 5612. [CrossRef] [PubMed]
77. Donahue, R.J.; Lumley, R.N. Chapter 6—New Hypoeutectic/Hypereutectic Die–Casting Alloys and New Permanent Mould Casting Alloys That Rely on Strontium for Their Die Soldering Resistance. In *Fundamentals of Aluminium Metallurgy*; Lumley, R.N., Ed.; Woodhead Publishing: Cambridge, UK, 2018; pp. 173–215.
78. Service Training. The Audi 4.0l V8 TFSI Engine from the EA825 Series. Audi of America, LLC. Created 2/2020 Course Number 920493. Available online: https://static.nhtsa.gov/odi/tsbs/2020/MC-10172005-0001.pdf (accessed on 17 June 2026).
79. Innovations for Sustainable Mobility. MAHLE International GmbH. Available online: https://newsroom.mahle.com/press_media/press/brochures/innovations-for-sustainable-mobility-2025/mahle_innovations_for_sustainable_mobiliy_en.pdf?download= (accessed on 17 June 2026).
80. Performance Engine Parts and Kits. Catalog No. X–3009. 2015. Federal–Mogul Corporation. Available online: https://www.drivheavydutyparts.com/content/dam/marketing/North-America/catalogs/speed-pro/pdf/speed-pro-performance.pdf (accessed on 17 June 2026).
81. UEM Pistons & Rings. Catalog Supplement 2024. United Engine and Machine Co. Available online: https://uempistons.com/sites/default/files/Supplement_Catalog.pdf?utm_source=chatgpt.com (accessed on 17 June 2026).
82. Sanders, R.; Kiefer, W. Aluminum Alloys, Recycling, and the Circular Economy. In *Applied Circular Economy Engineering*; Araujo, J.B., Hinderer, H., Viere, T., Woidasky, J., Eds.; Wiley: Hoboken, NJ, USA, 2025; pp. 21–42.
83. Bukvić, M.; Vencl, A.; Milojević, S.; Skulić, A.; Gajević, S.; Stojanović, B. The Influence of Carbon Nanotube Additives on the Efficiency and Vibrations of Worm Gears. *Lubricants* **2025**, *13*, 327. [CrossRef]
84. Ghasemi, S.M.S.; Azizi, A. Alkaline leaching of lead and zinc by sodium hydroxide: Kinetics modeling. *J. Mater. Res. Technol.* **2018**, *7*, 118–125. [CrossRef]
85. Aboulkhair, N.T.; Everitt, N.M.; Ashcroft, I.; Tuck, C. Reducing porosity in AlSi10Mg parts processed by selective laser melting. *Addit. Manuf.* **2014**, *1–4*, 77–86. [CrossRef]
86. Lu, L.; Dahle, A.K. Effects of combined additions of Sr and Al–5Ti–1B grain refiner on the microstructure and properties of hypereutectic Al–Si alloys. *Mater. Sci. Eng. A* **2006**, *435–436*, 288–296. [CrossRef]