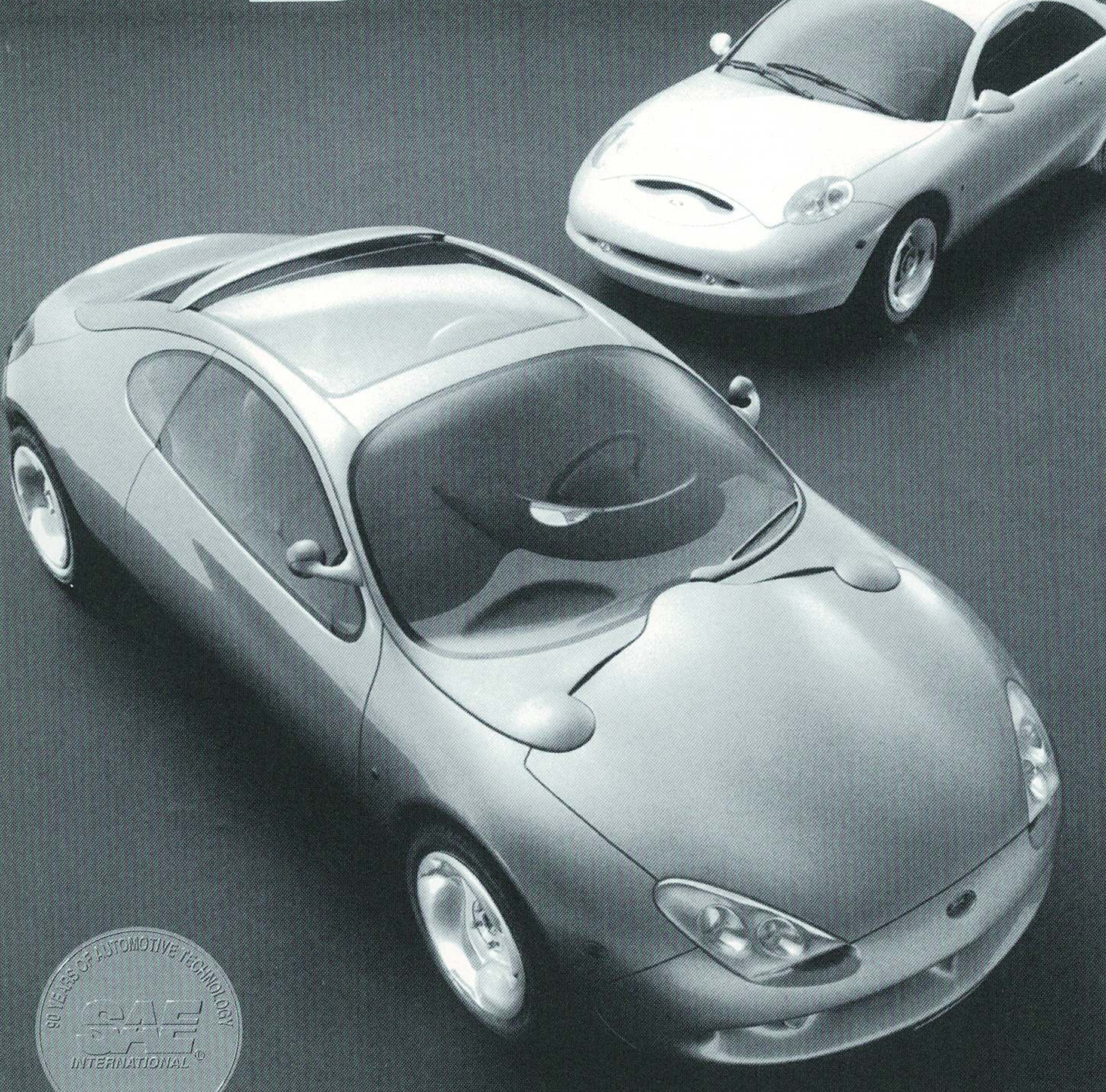
JANUARY 1995 SAE '95 PREVIEW

automotive engineering



90 YEARS OF AUTOMOTIVE TECHNOLOGY
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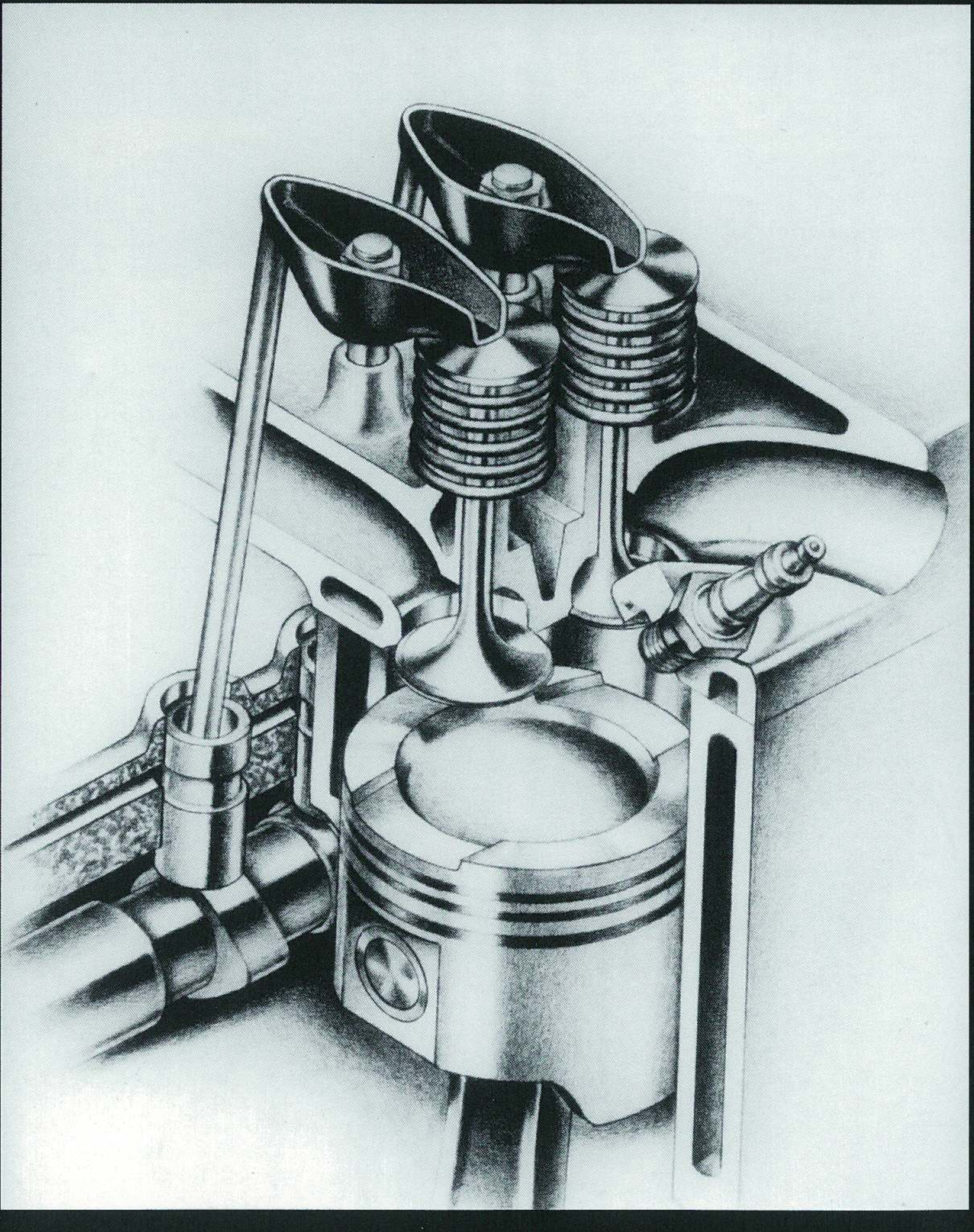

Engine performance improvements

Nickel ceramic coatings (NCC) hold promise for assisting material and design engineers in the production and commercialization of lightweight, fuel-efficient aluminum engines.

Fuel economy improvement, one of the most prominent challenges facing the automotive industry, has prompted considerable effort toward developing more fuel-efficient vehicles. Two major variables impacting fuel economy are vehicle weight and friction loss. Reduced friction, along with an accompanying reduction in vehicle weight, can lead to significant fuel-efficiency improvements.

Considering the effects of these factors, investigations of available technologies which enable the effective use of lightweight materials is of prime importance. Surface modifications capable of combating friction loss will play important roles in engine R&D work related to fuel economy.

Automotive technology and fuel economy

The two major routes to improving fuel economy are improvement in powertrain efficiency and reduction of acceleration and rolling resistance. The governing technologies in these categories are:

- (1) Improvement of powertrain efficiency
  - (a) Efficiency of engine combustion
  - (b) Reduction in friction loss
  - (c) Improvement of power transfer efficiency
- (2) Reduction of acceleration and rolling resistance
  - (a) Weight reduction
  - (b) Improvement of aerodynamics
  - (c) Reduction of rolling resistance.

Vehicle weight is the biggest factor directly affecting fuel economy. In spite of the considerable shift away from iron-based materials to polymers and lightweight metals, continued emphasis must be placed upon making further weight reductions to achieve still greater gains in fuel economy.

In addition to body panels and the vehicle chassis, the engine itself contributes significantly to total vehicle weight. Engine blocks, the largest engine component, have traditionally been produced from cast iron. The shift from cast iron to aluminum engine blocks has created a need for surface engineering technologies capable of overcoming performance deficiencies inherent to aluminum. As this material-substitution trend continues, further research will be required to develop optimum surface-modification technologies to ensure the longevity of all mating engine components.

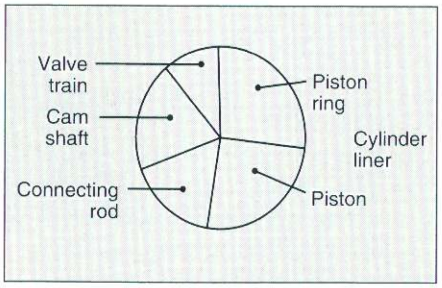

Figure 1. Breakdown of friction losses by engine components.

In engine systems, friction accounts for a loss of over 40% of total power. Over half of this power loss is attributable to friction between pistons, piston rings, and cylinder bores as illustrated in Figure 1.

Methanol fuel

Limitations in fossil-fuel reserves have necessitated efforts to develop alternative energy sources and fuel substitutes for gasoline. These include natural gas, LPG, and alcohols. Various alcohol-fueled engine test results have validated the need for development of wear- and corrosion-resistant materials to be used in conjunction with these fuels as indicated in Table 1.

Aluminum engine technologies

Cast iron has traditionally been the most common engine block material, due to its economic advantages and ease of processing. In the recent past, various lightweight aluminum alloys (e.g., high Si-Al alloys/390) have been developed and applied in engine block and piston applications for vehicle production.

Global environmental and ecological concerns are now forcing automotive manufacturers to develop vehicles having still greater fuel efficiency. These environmental concerns have escalated the importance of devising technologies suitable to the mass production of all-aluminum engine blocks having sufficient power and extended life capabilities. R&D efforts focusing on use of lightweight materials and surface-modification technologies have enabled the attainment of objectives for all-aluminum engines.

Of the four-stroke aluminum-block engines on the market, many rely upon the use of cast iron liners. This design affords ~30% weight reduction. Mating piston and piston-ring materials have proven histories of success showing acceptable wear and seizure properties against cast iron liners. As such, use of cast iron liners represents one viable alternative to support the use of aluminum engine blocks.

Achieving an optimum balance of wear and abrasive properties between all mating cylinder components requires investigation of several mating material combinations. Alternatives having high potential to contribute towards viability of all-aluminum engines are as follows:

Table 1
Component Wear in Methanol-fueled Otto-cycle Engines

Items	Parts name	Unit	Gasoline	Methanol (M93)
Ring wear	1st ring	mg	15.5	107.9
Ring wear	2nd ring	mg	2	36.7
Cyl. wear	Top zone	µm	50	—
Ring gap	Top	µm	50	230
Ring gap	2nd	µm	50	150
Brg. wear	Rod brg.	mg	91	177.8
Brg. wear	Main brg.	mg	46.6	145.8
Valvetrain	Cam lifter	µm	79	210
Oil consump.		liters	3.4	7.0
Test distance		x 1000 km	12.4	10.5

(1) Development of materials or surface modification methods enabling effective use of high Si-Al alloys for pistons and/or cylinder bores. In this case, appropriate surface modification methods (electroplating or heat treating) should be employed to impart optimum properties for cylinder bores, pistons, and piston rings.

(2) Development of composite technologies to improve strength and wear properties of hypoeutectic (low Si-Al) aluminum alloys. Candidate technologies for this case include fiber or particle reinforcement as developed and applied by Toyota and Honda. Other methods include use of reinforced materials for cast-in or inserted liners, or forged pistons.

(3) Application of electroplated, composite-coated surface-modification methods for cylinder bores, pistons, and piston rings.

(4) Application of composite polymer coatings containing solid lubricants to piston and piston-ring components primarily for purposes of reduced friction.

High-silicon aluminum alloys—Hypereutectic alloys, such as the 390 group, have excellent wear- and thermal-resistance properties. However, 390 aluminum suffers the drawbacks of poor castability and machinability compared to cast iron and hypoeutectic aluminum alloys. Further, attack by primary silicon particles upon mating materials can be problematic, depending upon the shape and distribution of those particles.

To achieve effective use of hypereutectic high silicon alloys for cylinders or other wear components, control of the as-cast microstructure is crucial. This can be achieved via control of solidification rate, improvements in the casting process, and analytical simulation of the alloy.

Bore finishing methods such as electrochemical machining (ECM) and plateau honing (PH) also largely impact the cylinder bore oil film condition. This condition should be closely reviewed to ensure optimum wear properties and component performance.

Pistons and piston rings running in conjunction with hypereutectic aluminum alloy engine blocks require effective surface modification to ensure adequate component life expectancy. This can be achieved through the use of methods such as hard chromium electroplating (HCEP), plasma spray (PS) coating, nitriding, nickel-based composite electroplating, or physical vapor-deposited titanium nitride coatings (PVD-TiN).

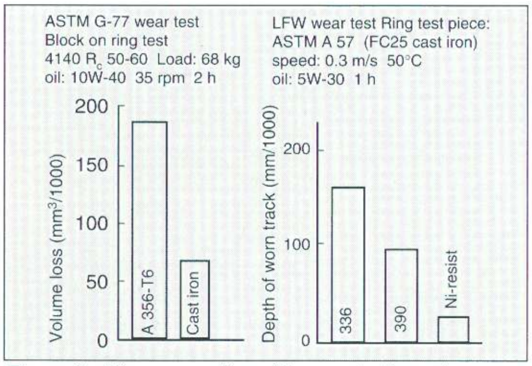

Figure 2. Wear properties of hypoeutectic and hypereutectic alloys.

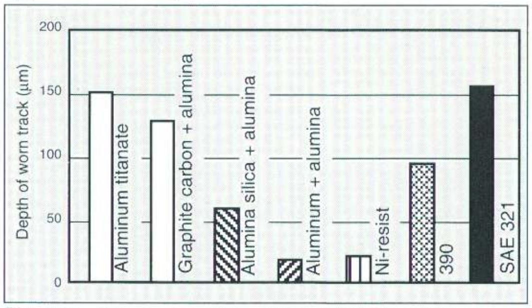

Figure 3. Wear properties of FRM piston material (conditions of LFW test in Figure 2).

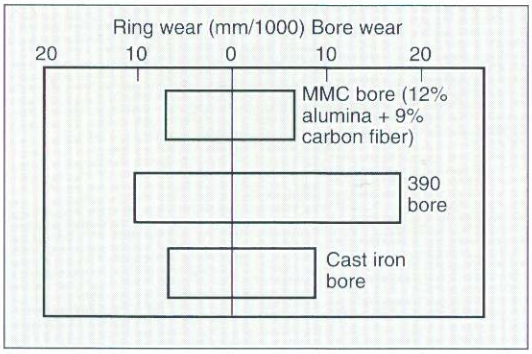

Figure 4. Wear properties of MMC cylinder bore and piston rings (80,450 km fleet durability test).

Hypoeutectic aluminum alloys—Use of low- or medium-silicon aluminum alloys for engine components requires the development of economical mass-production technologies which impart sufficient surface wear properties to cylinder bores. Availability of viable metallurgical or surface modification technologies allow for greater application of lightweight hypoeutectic aluminum engine components. Figure 2 provides a comparison of wear properties of hypoeutectic and hypereutectic alloys.

Fiber- or particle reinforced aluminum alloys—Use of fiber- or particle-reinforcement technology has expanded gradually since 1981. Alumina-silica fiber reinforced aluminum pistons represented the first such technology applied for mass-production vehicles. Today, various types of particle-reinforced composite aluminum materials are being investigated, but have yet to be applied in mass-produced automotive components.

Fiber reinforced metal (FRM) piston—Diesel engine pistons produced from wrought or squeeze-cast aluminum alloys have traditionally required application of cast-in, Ni-resist inserts. A newer technology, gaining wide acceptance in Japan, is use of FRM pistons which improves top-ring-groove wear properties as illustrated in Figure 3.

Toyota Motor Corporation developed a fiber-reinforced-metal (FRM) technology which has been applied for diesel-engine pistons since 1981. The first generation FRM technology involved squeeze casting 6-7 vol% of the least expensive ceramic-fiber preforms into top ring grooves of diesel pistons. Since that time, FRM wear properties have been continually improved via upgrading the quality of reinforcing fibers used. Presently, all ten types of diesel engines manufactured by Toyota Group companies are applying FRM pistons, with total production running ~3,000,000 pieces per year.

FRM bore (MMC engine block)—Honda Motor has pioneered the use of FRM bores in aluminum engine blocks. Since 1988, Honda has employed cast-in FRM bores on its 1958-

cc, four-cylinder engines. Use of FRM bores has resulted in reduced cylinder deformation, along with positive bore and ring wear properties. Figure 4 provides a comparison of wear properties of MMC cylinder bores vs. 390 and cast iron.

Surface modification technologies—Alternatives to the use of FRM technologies to increase viability of components produced from low- to medium-Si-Al alloys include a variety of surface-modification methods such as HCEP, explosive spray coatings (ESP), plasma spray coating, and composite electroplating methods.

Successful developments with these technologies have enabled the use of low-Si-Al alloys for several production engines. Among these are several passenger cars' gasoline engines, and two-stroke motorcycle engines. Successful application of these technologies has afforded cylinders, pistons, and piston rings the necessary wear resistance to make these material/surface-modification combinations viable.

Specifically, nickel- or iron-based composite electroplating technologies have been investigated since the early 1970s. These technologies are presently applied on a variety of small two-stroke motorcycle, outboard marine, snowmobile, and limited luxury passenger car engine components. Nickel-based platings have been used for cylinders and piston rings, while iron- or nickel-based platings are used for piston applications.

Recent breakthroughs in the use of composite electroplating surface modification technologies are based upon the addition of phosphorous to nickel or iron coating base matrices for enhancement of film hardness.

Nickel ceramic composite coatings (NCC)

As an alternative to the use of hypereutectic Al-Si alloys such as 390 and Mercosil, application of a variety of hypoeutectic alloys is becoming possible via the development of superior electroplating methods for surface modification. Presently, Nikasil plating (electroplated nickel with silicon carbide ceramic) is being applied to Honda (motorcycle), BMW, Jaguar, Mercedes-Benz, and other limited passenger car and Formula 1 engine cylinder bores. NCC coatings with silicon carbide or boron nitride are being applied to Suzuki, Yamaha, and Kawasaki two-stroke motorcycle, marine, and snowmobile engines, as well as to a limited number of race car engines.

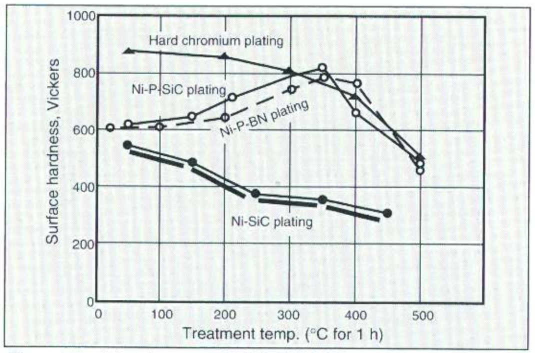

Figure 5. Hardness of NCC, Ni-SiC, and hard chrome plating as a function of high-temperature exposure.

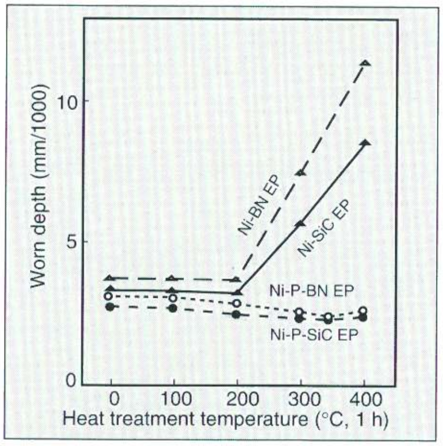

Figure 6. Impact of phosphorus on wear properties of nickel-based coatings. (Ultra-high pressure wear tester, block & ring Cr-plated cast iron, 1 h.)

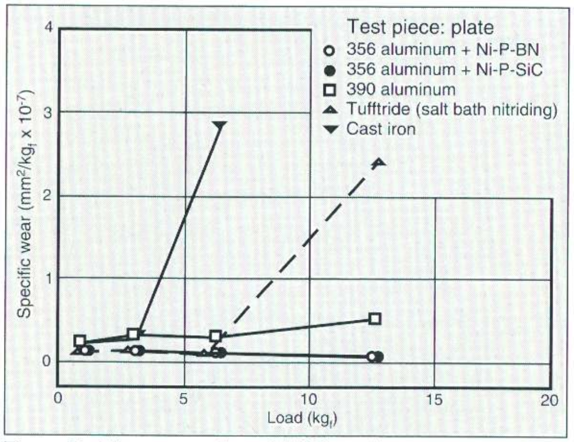

Figure 7. Wear properties of NCC coatings.

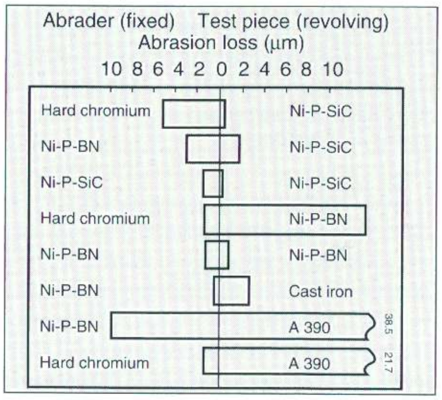

Figure 8. Wear test results of NCC coating with various material combinations (150 kg/cm², 0.5 m/s, 5 km).

NCC and Nikasil electroplated coatings use ceramic dispersants to improve surface properties. Both Nikasil, as well as a portion of the NCC-type coatings, contain silicon carbide ceramic particles to improve wear properties.

Alternative NCC coatings include boron nitride (BN) for its superior self-lubricating properties, and silicon nitride (Si_3N_4) for its combination of wear resistance and self-lubrication.

Self-lubricating properties afforded by the use of BN and Si_3N_4 also offer greater flexibility in selection of mating materials while increasing the potential to tighten tolerances between mating components. Additionally, both NCC and Nikasil coatings exhibit superior corrosion resistance over alternative electroplating technologies, allowing their use in hostile diesel- and methanol-fuel environments.

NCC coating, due to the high hardness afforded by its phosphorous-containing, nickel-base matrix, is suited to operate even under the most severe operating conditions. The hardness of the NCC coating film increases upon exposure to elevated temperatures as illustrated in Figure 5. Conversely, nonphosphorous-containing electroplated nickel films experience a decrease in hardness upon exposure to high operating temperatures, due to a softening of the pure nickel base matrix.

Figure 6 illustrates the vast differences in wear properties between phosphorous-containing and nonphosphorous-containing nickel-based coatings as a function of temperature. Phosphorous-containing NCC coating exhibits superior high-temperature wear properties irrespective of the type of ceramic dispersant present in the plated film.

Figure 7 demonstrates the superior wear properties exhibited by NCC coatings plated onto hypoeutectic aluminum compared to AC9A (390), nitrided (Tufftrided) ferrous-based materials, and FC20-G3000 (cast iron).

Attaining optimum wear- and abrasion-resistance properties requires investigations of many types of material combinations, as wear properties are largely a function of mating materials. Figur 8 shows the wear-test results of various combinations of materials and surface modifications. In most cases, NCC coatings offer superior wear resistance as compared to 390 alloys and hard chromium EP.

NCC-SiC and NCC-BN are characterized by different sets of properties. Silicon carbide (SiC) exhibits high hardness, affording superior wear properties. Boron nitride (BN) exhibits excellent self-lubricating properties. This allows for NCC-BN to be run under highly loaded, limited-lubrication conditions without experiencing wear while resisting seizure. Test results from Figure 8 indicate that the best wear properties are achieved using NCC:NCC combinations. Although the laboratory-generated data of Figure 8 do not present any recommended mating materials for running in conjunction with hypereutectic 390 aluminum, actual engine testing has revealed that NCC-BN pistons have a high degree of compatibility with this alloy.

In addition to high hardness and corrosion resistance, the most effective property of NCC coating is its low frictional coefficient. As such, NCC is capable of contributing significantly to the reduction of friction between sliding components. The friction coefficient of NCC coatings falls in the 0.08-0.12 range, even under nonlubricated conditions. As Figure 9 demonstrates, these values are much lower than those of hard chromium plating (0.28-0.48). As stated earlier, NCC coating with boron nitride (BN) exhibits superior frictional properties under nonlubricated, high-load conditions because of the self-lubricating nature of hexagonal boron nitride ceramic.

By properly modifying pretreatment processes, NCC coatings can be applied to a variety of materials such as titanium, magnesium, plain carbon steels, and cast iron. Figure 10 shows frictional coefficients for several types of NCC coatings plated over titanium 6Al-4V. These frictional coefficient ranges of 0.10-0.12 under lubricated conditions fall well below values characteristic of uncoated titanium alloys, which are in the 0.36-0.38 range.

Technologies for all-aluminum engines

One of the most important tasks facing the global automotive industry is the development of viable all-aluminum engines. Accomplishing this is critical from the standpoint of being able to meet the ever-more-stringent exhaust-emissions requirements, CAFE standards, and for preservation of the global ecology.

In spite of the effort devoted to investigations of the feasibility of mass producing all-aluminum engines, several technical problems require resolution to make the economical mass production of durable, high-performance engines feasible. Hypereutectic Al-Si alloys represent prime candidate materials for use in all-aluminum engine blocks. However, use of these alloys requires application of effective surface-modification techniques to be used on piston and piston-ring components. Appropriate surface modifications applied to these components ensure the viability of wear and abrasion properties on these components to be run in conjunction with potentially abrasive high-silicon blocks.

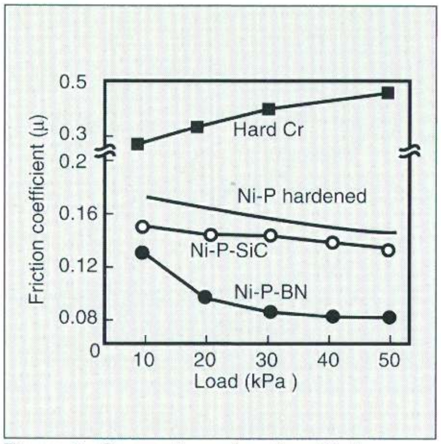

Figure 9. Comparison of surface friction coefficients (rigid ball—52100—type friction tester).

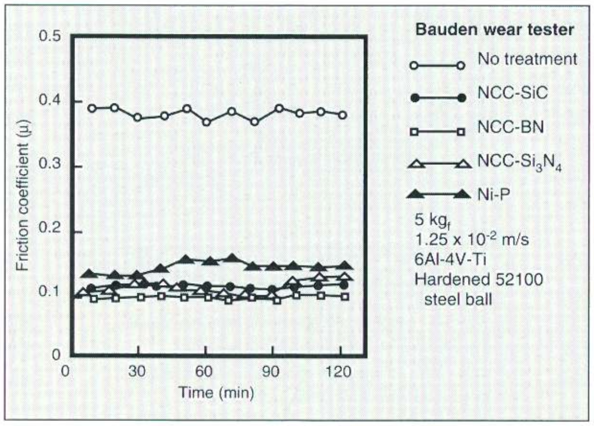

Figure 10. Comparison of surface friction coefficients of NCC on titanium alloys.

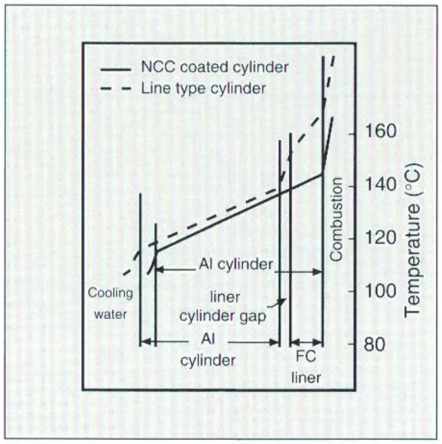

Figure 11. Improvement of temperature distribution in case of linerless NCC-coated cylinder bore.

The use of high-Si-Al alloy engine blocks also requires that the size and distribution of primary-silicon particles be fine in nature and uniformly dispersed. Doing so can significantly improve block machinability while balancing wear on mating components, thereby maximizing component wear life.

Alternatively, the use of low-Si-Al hypoeutectic aluminum alloys requires that superior surface-modification methods be imparted to the cylinder-bore surface to improve wear properties.

Application of NCC coating

NCC coating can be applied to both aluminum liners and aluminum cylinder bores. Application of NCC coating to cylinder bores is done via either the conventional immersion process or by use of the recently developed flow-through plating process.

The NCC flow-through process is designed to accommodate the plating of both in-line and V-design four-stroke engines on a high-volume basis within OEM engine manufacturing facilities. It is believed that the costs associated with use of this process have the potential to be comparable to those characteristic of cast-in iron liners while allowing for the obvious benefits associated with elimination of cast iron liners.

The effectiveness of NCC coating on four-stroke gasoline engines has been proven in many race-engine applications. Due to its ability to operate at high temperatures, in corrosive environments, its low frictional coefficient, and its nonattack properties, NCC coating is under consideration as a candidate material for many new engine designs. This is particularly true for engines to be run under demanding conditions.

NCC coatings have been applied on Suzuki two-stroke all-aluminum engines for motorcycle, marine, and snowmobile applications for nearly ten years. NCC is also applied in Yamaha and Kawasaki two-stroke engine cylinder bores and pistons. Recently, use of NCC has been extended to 4-stroke engine cylinder bores within the Yamaha and Suzuki product lines, attesting to the utility that NCC affords in the four-stroke engine regime. Thus a solid experience base has been generated in applying NCC coating on a mass-production basis.

In the cases stated above, both silicon carbide (NCC-SiC) and boron nitride (NCC-BN) are being applied. NCC with silicon nitride (Si_3N_4) is also given serious consideration due to its unique combination of wear resistance and high lubricity.

Direct application of NCC coating on cylinder bores allows for elimination of cast iron liners. A prime benefit derived from this is illustrated in Figure 11. Absence of cast iron liners contributes to an improvement in thermal distribution while reducing cylinder-wall temperature, due to the enhanced thermal conductivity of the NCC-coated aluminum surface adjacent to the combustion chamber.

Elimination of cast iron liners also affords flexibility in the following design areas:

- Reducing length of engine components (e.g., engine block, crankshaft, camshaft) for weight-reduction purposes and fuel-economy improvement.
- Increasing engine displacement for greater power.

An example, depicting potential benefits associated with use of NCC coating, is presented in Figure 12. Oil consumption in engines employing NCC coatings is significantly reduced as a result of improved clearances and wear life.

With respect to friction-reducing capabilities, Figure 13 demonstrates that increases of 3.5% in torque and power have been achieved through the use of NCC-BN coatings on aluminum cylinder bore surfaces. These gains are made possible due to the self-lubricating nature of hexagonal boron nitride ceramic under high-load, sliding conditions.

In general, use of NCC coatings on engine cylinder-bore surfaces makes possible the running of tighter piston/cylinder clearances while lowering oil consumption, emissions, wear, and friction loss.

NCC-coated pistons

Piston-ring grooves and piston skirts represent the two most challenging areas on pistons in terms of ensuring appropriate function while operating under increasingly higher demand conditions.

Piston compression-ring grooves are gradually being forced to operate at higher temperatures to enable successful reduction in emissions due to reduced crevice volume. Doing so, however, creates a high degree of susceptibility to ring-groove microwelding. Proven materials solutions to combat ring-groove microwelding under these high-temperature conditions include anodized piston-ring grooves and composite polymer-coated piston-ring side faces.

Ongoing efforts to reduce NVH have resulted in much emphasis being placed on reducing piston-skirt/cylinder-bore clearances. Clearance tightening has demanded that frictional properties between the piston and cylinder bore be much improved. Use of composite polymer-coated piston skirts has proven most effective in this capacity and shows much potential for widespread incorporation into automotive engine product lines.

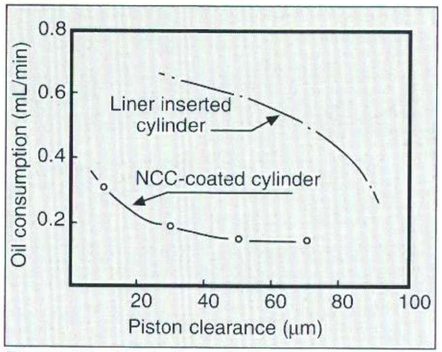

Figure 12. Reduction of oil consumption via use of NCC-coated bore.

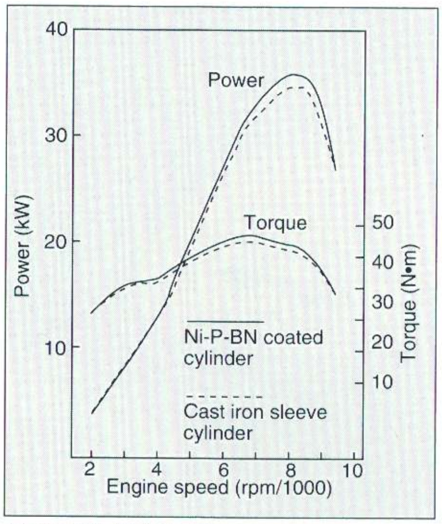

Figure 13. Motorcycle power curves.

The benefits derived from historical use of NCC coating on reciprocating-engine pistons in Japan creates potential for incorporation of a "single solution" to address the piston ring-groove and skirt concerns described. Specifically, NCC is now applied on two-stroke motorcycle pistons in ring-groove regions to address microwelding problems. Additionally, applications involving NCC-BN (high-lubricity ceramic) coated piston skirts have yielded extremely low wear, scuff, and friction loss coupled with measurable power increases, thereby creating promise for this coating to operate successfully under "tight fit" conditions (see Figure 8—NCC-BN vs cast iron).

NCC-coated pistons have also proven effective in providing secondary benefits on piston domes. The presence of this hard, nickel-based material has shown to be resistant to carbon deposition on piston domes and upper piston lands. Benefits are reduced emissions, along with reduced sensitivity to "knock" and "ring jacking." NCC has also been shown to be effective in its capacity as a thermal barrier coating on piston domes.

In general, although several viable surface-modification methods exist to address piston-related concerns associated with higher demand conditions, much potential exists for application of NCC-coated pistons to address these concerns simultaneously while optimizing piston performance—irrespective of cylinder bore material.

NCC vs. Fe-P coated pistons—While the high hardness of Fe-P coatings (~Hv 1000) allows for good wear properties, NCC coating provides some distinct advantages over Fe-P-based coatings on pistons.

NCC coatings affords friction reduction properties superior to those of Fe-P coatings. Additionally, while Fe-P coatings typically require the use of tin flash coatings to improve scuffing resistance during break-in periods, NCC coatings require no break-in coatings. Further, the corrosion resistance properties of NCC coatings make them better suited than Fe-P coatings to function in potentially corrosive environments or those employing the use of low-grade or alcohol fuels.

Piston-ring coatings—Japanese piston-ring manufacturers have been successful in applying various modified versions of the traditional NCC coating to piston-ring barrel surfaces. Adjustments in concentration of traditional constituents impart higher hardness to the as-plated films. The enhanced properties created allow these coatings to act as excellent top coatings over chrome-plated or nitrided piston rings to ensure optimum break-in, thereby significantly improving the wear balance between rings and cylinder bores over a greater life expectancy. As such, the combination of NCC coatings on both pistons/piston rings and cylinder-bore surfaces offers much potential in improving the wear balance and frictional properties of all-aluminum engine blocks.

Summary

Production of lightweight, fuel-efficient vehicles is largely dependent upon use of aluminum engines. Successful use of aluminum engine blocks, in turn, relies upon effective means of surface modification to impart properties not inherent to aluminum alloys. Many such surface-modification technologies exist which have the potential to contribute towards this end. Electroplated nickel-phosphorous-based ceramic composite coatings (NCC coatings) have proven to be effective.

NCC coatings impart various desirable combinations of surface properties to engine components such as cylinder bores, liners, pistons, and piston rings. These properties and corresponding benefits include:

- Elimination of cast iron liners, enabling weight reduction and lowering of cylinder-wall temperatures.
- Reduced friction, enabling increases in power, torque, and fuel economy.
- Superior wear and scuff properties enabling effective combating of ring-groove microwelding and optimum wear balance between piston skirts and cylinder bores.
- Reduced noise, due to capabilities to run tighter cylinder-to-piston clearances, and reduced oil consumption.
- Excellent corrosion resistance, coupled with resistance to carbon deposition and thermal barrier protection on piston domes.

Although NCC coating technology was developed and established in the two-stroke, small-engine market, its compatibility with larger four-stroke and diesel-engine components is high. As such, NCC coating holds much promise for assisting reciprocating-engine materials and design engineers as they seek to produce and commercialize lightweight, fuel-efficient aluminum engines.

Information and illustrations for this article were supplied by **K. Funatani** and **K. Kurosawa**, of Nihon Parkerizing Co., and **P. A. Fabiyi** and **M. F. Puz**, Daubert Chemical Co.