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Improved Engine Performance Via Use of Nickel Ceramic Composite Coatings (NCC Coat)

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ABSTRACT

In seeking to produce lightweight aluminum block based engines, a variety of metallurgical and surface modification techniques for cylinder bores, pistons and piston rings are available. This paper discusses these various alternative methods while placing particular emphasis on electroplated nickel ceramic composite coatings (NCC). NCC Coating properties are characterized by high hardness, high corrosion resistance, high temperature wear and scuff resistance and low frictional coefficients.

The application of NCC Coatings in 2-stroke motorcycle and diesel engines has resulted in benefits in the following areas:

- Elimination of cast iron liners.
- Reduced cylinder wall temperature, engine weight and increased power.
- Lowering of oil consumption.
- Improved fuel economy.
- Reduction in emissions.
- Improved scuff and wear resistance on cylinder bores, pistons and piston rings.
- Friction reduction.
- Combating of piston ring groove microwelding and pound out.
- Thermal barrier protection on diesel piston domes.
- Reduction in carbon deposition on piston domes.
- Reduced noise from piston slap.
- Ability to operate in corrosive environments.

The sum of the above stated benefits holds much potential for contributing towards greater flexibility in materials selection for the design of lightweight, fuel efficient vehicles based upon the use of aluminum engines.

1. INTRODUCTION

Fuel economy improvement, as one of the most prominent challenges facing the automotive industry, has prompted considerable efforts to be devoted to 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 improvements in fuel efficiency.

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 research and developmental work related to fuel economy. This paper focuses on materials and surface modification methods as they pertain to improving performance of engine cylinder components.

2. 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 effecting fuel economy. In spite of the considerable shift away from iron based materials to polymers and lightweight metals to date, continued emphasis must be placed upon making further weight reductions to achieve still greater gains in automotive fuel economy.

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

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

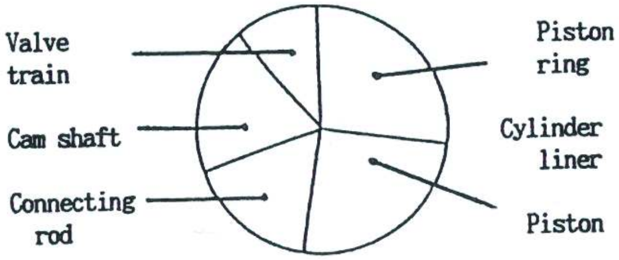


Figure 1: Breakdown of friction loss for engine components (1).

3. METHANOL FUEL

Limitations in fossil fuel reserves has necessitated research and development efforts to develop alternative energy sources and fuel substitutes for gasoline. These substitutes include natural gas, LPG and alcoholic fuels. 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 (2).

Table 1: Component wear in methanol fueled Otto engines.

ITEMS	PARTS NAME	UNIT	GASO-LINE	METHANOL M93
Ring wear	1st ring	mg	15.5	107.9
Ring wear	2nd ring	mg	2	36.7
Cyl. wear	Top zone	micron	50	---
Ring gap	Top	"	50	230
Ring gap	2nd	"	50	150
Brg wear	Rod Brg	mg	91	177.8
Brg wear	Main Brg	"	46.6	145.8
Vv Train	Cam Lifter	micron	79	210
Oil consum.		liters	3.4	7.0
Test dist.		x1000km	12.4	10.5

4. STATE OF ALUMINUM ENGINE TECHNOLOGIES

Cast iron has traditionally been used as the most common engine block material due to its economic advantages and ease of processing. In the recent past, various lightweight aluminum alloys (eg., 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. Research and development efforts focusing on use of lightweight materials and surface modification technologies have enabled the attainment of objectives in the case of all aluminum engines.

Of the several 4-stroke aluminum block engines on the market, many rely upon the use of cast iron liners. This design affords an approximate weight reduction of 30 percent. 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.

(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 Motors. 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.

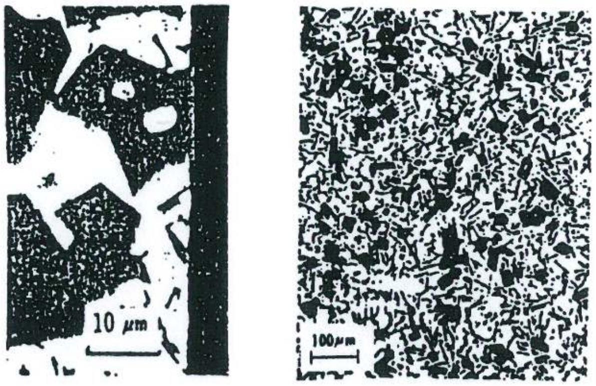
(4) As a complement to the above stated surface modification methods, application of composite polymer coatings containing solid lubricants can further enhance frictional properties of engine components.

4.1 HIGH SILICON ALUMINUM ALLOYS - Hypereutectic alloys, such as 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 the primary silicon 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 (4). Figure 2 demonstrates the microstructure of primary silicon crystals and an electrochemical machined surface of a hypereutectic aluminum alloy. Dark grains represent primary silicon crystals.

Bore finishing methods such as electrochemical machining (ECM) and plateau honing (PH) also largely impact the cylinder bore oil film condition (3). This condition should be closely reviewed to ensure optimum wear properties and component performance.



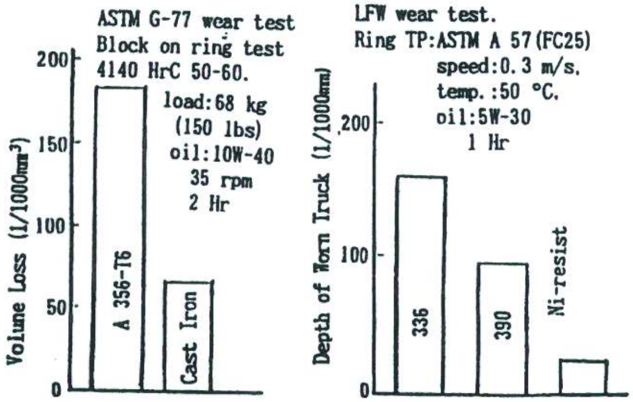
Primary silicon grain after ECM(3)

Typical primary Si distribution

Figure 2: Microstructure of primary silicon crystals.

Piston 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 coating (PC), nitriding, nickel-based composite electroplating or physical vapor deposited titanium nitride coatings (PVD-TiN).

4.2 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. Availability of viable metallurgical or surface modification technologies allow for greater application of lightweight hypoeutectic aluminum engine components. Figure 3 provides a comparison of wear properties of hypoeutectic and hypereutectic alloys (5,6).



a) ASTM G-77 wear test(5) LFW wear test(6)

Figure 3: Wear properties of hypoeutectic and hypereutectic alloys.

4.2.1 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.

1) Fiber Reinforced Metal (FRM) piston:

Diesel engine pistons produced from wrought or squeeze casted 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 4.

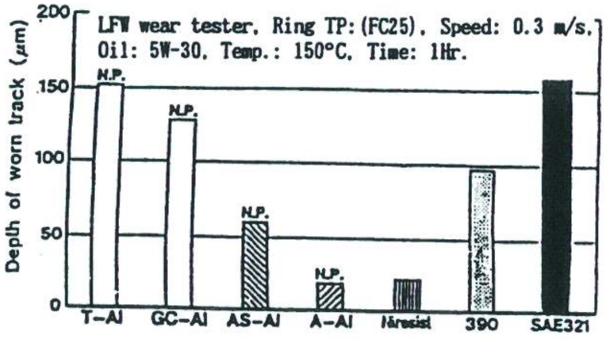
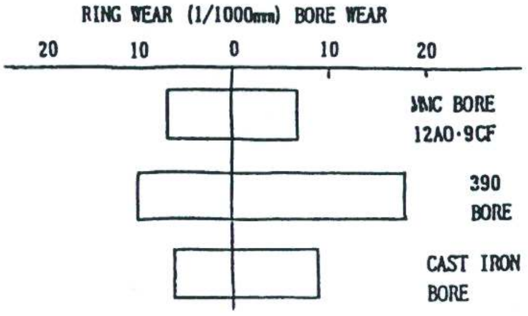


Figure 4. Wear properties of FRM Piston Material.

Toyota Motor Corporation has developed a fiber reinforced metal (FRM) technology which has been applied for diesel engine pistons since 1981 (6). The first generation FRM technology involved squeeze casting 6 to 7 volume percent 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 (7). Presently, all ten types of diesel engines manufactured by Toyota Group companies are applying FRM pistons with total production running approximately three million (3,000,000) pieces per year.

2) 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 their 1958 cc four cylinder engines. Use of FRM bores has resulted in reduced cylinder deformation along with positive bore and ring wear properties (8). Figure 5 provides a comparison of wear properties of MMC cylinder bores versus 390 and cast iron.



80,450 km (50,000 mile) fleet dura.test

Figure 5: Wear properties of MMC cylinder bore and piston rings.

4.2.2 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. These include HCEP, explosive spray coatings (ESP), Plasma spray coating (PS) 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 2-stroke motorcycle engines. Successful application of these technologies have 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 1970's. These technologies are presently applied on a variety of small 2-stroke motorcycle, outboard marine, snowmobile and limited luxury passenger cars 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 into nickel or iron coating base matrices for enhancement of film hardness.

5. NIHON PARKERIZING 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 are 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 Coating with silicon carbide or boron nitride are being applied to Suzuki, Yamaha and Kawasaki 2-stroke motorcycle, marine and snowmobile engines, as well as to a limited number of race car engines.

NCC and Nikasil electroplated coatings employ the use of 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 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 for their employment in hostile diesel and methanol fuel environments.

NCC coating, due to its high hardness afforded by its phosphorous-containing, nickel base matrix, is particularly 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 6. Conversely, non-phosphorous 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 (9).

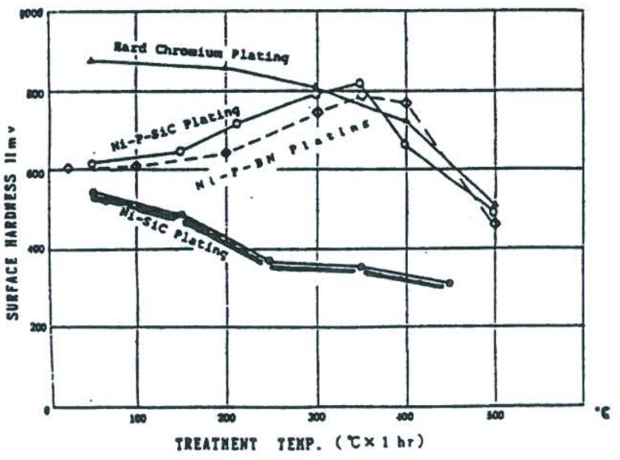
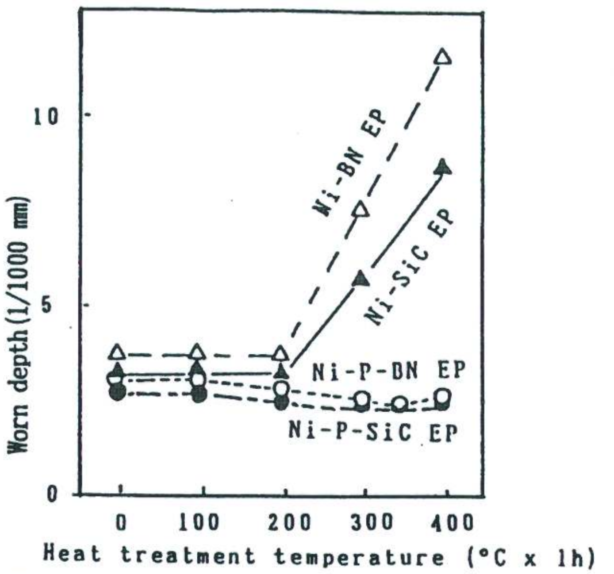


Figure 6: Hardness of NCC, Nikasil and hard chrome plating as function of high temperature exposure.



Ulta high pressure wear tester.
Block TP x Ring: Cr plated Cast Iron. Time:1 Hr.

Figure 7: Impact of phosphorous on wear properties on nickel based coatings.

Figure 7 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 8 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) (10).

Okoshi type wear tester.
Pre-wet Test Plate x Disc: Cr plated Cast Iron.
Speed: 4.2 m/s. Dist.:600 m

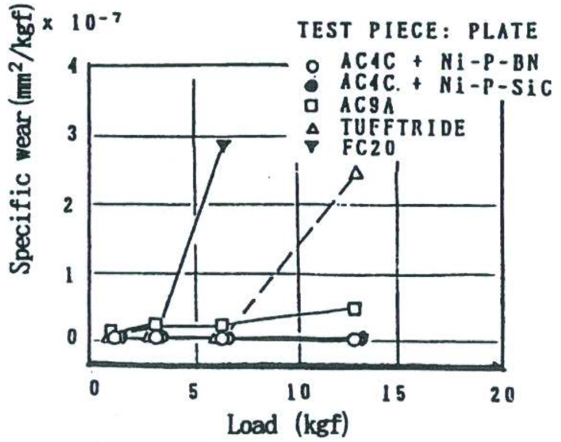
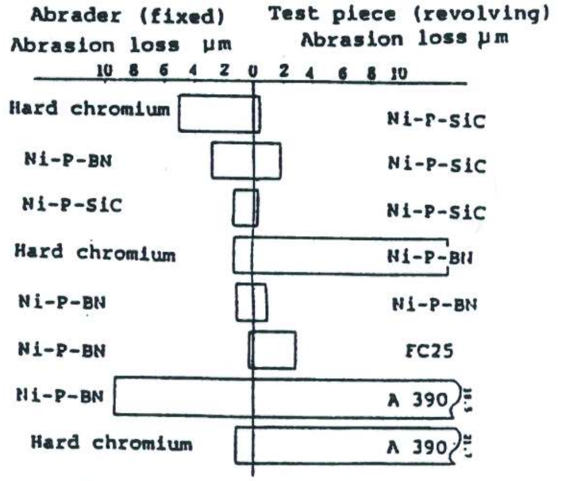


Figure 8: Wear properties of NCC coatings.

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.

Figure 9 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 HCEP.

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 9 indicate that the best wear properties are achieved using NCC:NCC combinations (9). Although Figure 9 does not present any recommended mating materials for running in conjunction with hypereutectic 390 aluminum, compatible NCC:390 combinations are possible via optimization of NCC ceramic type and phosphorous concentrations in the NCC film.

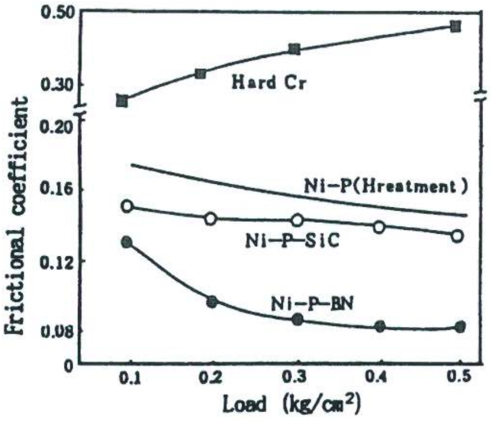


150 kg/cm², 0.5 m/sec (5 km)

Figure 9: Wear test results of NCC coating with various material combinations.

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 loss between sliding components. The friction coefficient of NCC coatings fall in the 0.08-0.12 range, even under non-lubricated conditions. As Figure 10 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 non-lubricated, 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 as titanium, magnesium, plain carbon steels and cast iron. Figure 11 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 fall in the 0.36-0.38 range (9).



Rigid ball (52100) type friction tester.

Figure 10: Comparison of surface frictional coefficients.

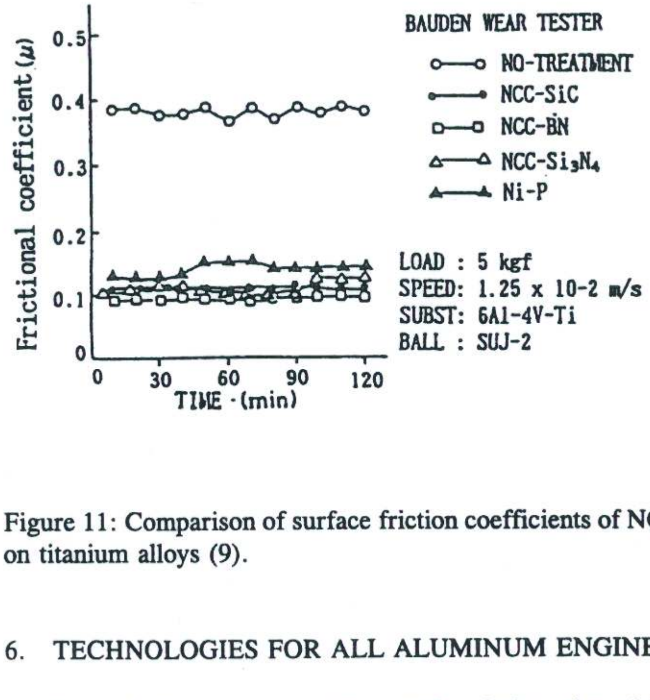


Figure 11: Comparison of surface friction coefficients of NCC on titanium alloys (9).

6. 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 task is critical from the standpoint of being able to meet the ever-more-stringent exhaust emissions requirements, CAFE fuel economy standards for the conservation of fossil fuels and for preservation of the global ecology.

To date, much work has been devoted to investigations of the feasibility of mass producing all aluminum engines. In spite of these efforts, several technical problems require resolution to make the economical mass production of durable, high performance engines feasible.

Hypereutectic Al-Si alloys represent a prime candidate material for use in all aluminum engine blocks. However, use of these aluminum alloys requires application of effective surface modification techniques to be applied to 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.

The use of high Si-Al alloy engine blocks also requires that 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.

6.1 TOYOTA ALUMINUM RECOMMENDATIONS(1)

Research and development studies conducted by Toyota Motor Corporation have generated recommended materials combinations and surface modification technologies having high potential for success in 4-stroke gasoline engines. Surface modifications recommendations for piston ring materials include use of nitriding, composite electroplating (phosphorous-containing) or PVD-TiN to improve hardness and wear properties.

Toyota has identified two viable alternatives enabling the use of aluminum engine blocks.

- Hypereutectic block with coated piston.
- Hypoeutectic block with surface modified cylinder liner.

In cases where hypereutectic aluminum engine blocks are employed, it is recommended that the surface of the piston skirt be coated by either an iron-phosphorous coating (Fe-P) or by some other comparable surface modification method such as NCC (Ni-P-ceramic) coating. Piston skirt coatings are necessary under these conditions to impart wear resistance for pistons running against high silicon containing cylinder walls.

In cases of hypoeutectic aluminum blocks, two alternatives for use of surface modified liners have been identified. One candidate combination is application of an NCC coated aluminum liner. The NCC coated liner should be coupled with a standard hypoeutectic aluminum alloy piston to guard against wear properties and potential seizure between the bore and piston.

The second liner alternative involves use of a cast-in metal matrix composite (MMC) liner into the hypoeutectic aluminum engine block. Under this scenario, the mating piston should be coated with either Fe-P electroplating or NCC coating for wear purposes.

For both of the above stated all aluminum engine block scenarios, wear of the piston ring should also be improved by application of nitrided steel rings, nickel-phosphorous containing composite coatings and/or PVD-TiN coating.

6.2 APPLICATION OF NCC COATING - NCC coating is capable of being applied to both aluminum liners or to aluminum cylinder bores. Application of NCC coat to cylinder bores is done via either the conventional immersion process or by use of the recently developed flow through plating process.

The flow through process is designed to accommodate the plating of both in-line and V-design 4-stroke engines on a high volume basis. Application of NCC coating directly on cylinder bores allows for elimination of reliance upon cast iron cylinder liners, as well.

Effectiveness of NCC coating on 4-stroke gasoline engines has been proven out on many race engine applications. Due to its ability to operate at high temperatures, in corrosive environments, its low frictional coefficient and its non-attack properties, NCC coating is being considered 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 Motor 2-stroke all aluminum engines for motorcycle, marine and snowmobile applications for nearly ten years. NCC is also applied in Yamaha and Kawasaki 2-stroke engine cylinder bores and pistons. As such, a solid experience base has been generated in applying NCC coating on a mass production basis.

In the case stated above, both silicon carbide (NCC-SiC) and boron nitride (NCC-BN) are being applied. As stated earlier, NCC with silicon nitride (Si_3N_4) is also being given serious consideration for application 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 12. Absence of cast iron liners contributes towards an improvement in thermal distribution while reducing cylinder wall temperature (12). This benefit is due to the enhanced thermal conductivity of the NCC coated aluminum surface adjacent to the combustion region.

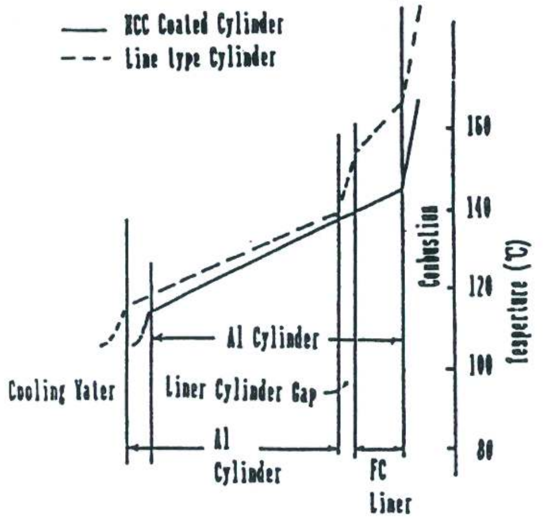


Figure 12: Improvement of temperature distribution in case of linerless NCC coated cylinder bore.

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

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

A vivid example depicting potential benefits associated with use of NCC coating is presented in Figure 13. Oil consumption in engines employing use of NCC coating is significantly reduced as a result of improved clearances and wear life. Additionally, increases of 3.5 percent in torque and power have been achieved through the use of NCC coating.

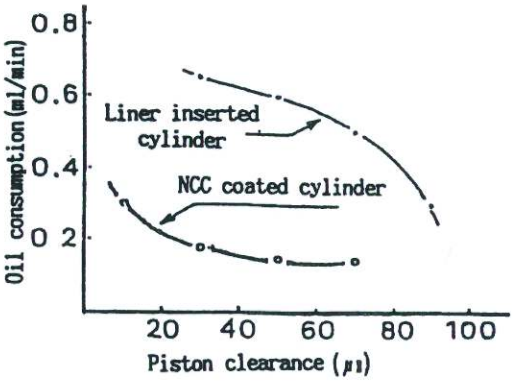


Figure 13: Reduction of oil consumption via use of NCC coated bore.

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 (12).

6.3 NCC COATED PISTONS - Application of NCC coating on piston skirts is very effective in both improving wear properties and reducing friction. NCC coated pistons have functioned extensively in this capacity in mass produced 2-stroke motorcycle engines. Additionally, NCC coating has proven effective in reducing carbon deposition on piston domes. Further, due to the heat resistant nature of the nickel-phosphorous matrix upon exposure to elevated temperatures, NCC coating has also been proven to be an effective thermal barrier coating on aluminum diesel engine piston domes (13).

6.3.1 NCC Versus Fe-P Coated Pistons - While the high hardness of Fe-P coatings (approximately Hv 1000) allows for good wear properties, NCC coating provides some distinct advantages over Fe-P based coatings on pistons.

NCC coating affords superior properties in friction reduction over 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 alcoholic fuels. Further still, it is believed that the presence of NCC coating in piston ring grooves contributes positively in combating the effects of microwelding and pound out.

6.4 PISTON RING COATINGS - Japanese piston ring manufacturers have been investigating various types of nickel-phosphorous based composite electroplatings. As explained in Section 5, one means of optimizing wear properties is accomplished via the mating of similar materials along the cylinder:piston/piston ring interface. Doing so can result in excellent wear properties and extended component wear life.

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.

7. 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 particularly effective in functioning in this capacity.

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:

1. Ability to eliminate cast iron liners enabling weight reduction and power increase.
2. Frictional reduction resulting in potential for increases in power/torque and flexibility in mating material selection.
3. Superior wear and scuffing properties on cylinder bores, piston skirts and piston rings.
4. Lowering of cylinder wall, piston and piston ring temperature.
5. Resistance to ring groove microwelding and pound-out.
6. Reduction of carbon deposition on piston domes.
7. Reduced piston noise from slap due to flexibility in tightening clearances.
8. Lowering of oil consumption.
9. Thermal barrier protection on diesel piston domes.
10. Ability to operate in corrosive diesel and low grade fuel environments.

Although NCC coating technology was developed and established in the 2-stroke small engine market, its compatibility with larger 4-stroke and diesel engine components is high. As such, NCC coatings holds much promise for assisting reciprocating engine materials and design engineers as they seek to produce and commercialize lightweight, fuel efficient aluminum engines.

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