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Manufacturing Feasibility of All- Aluminum Automotive Engines Via Application of High Silicon Aluminum Alloy

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ABSTRACT

Parent bore materials of copper-containing hypereutectic Al-Si alloys have been tried with limited success. Fundamentally the reason for this technology limitation is because copper-containing hypereutectic aluminum-silicon alloys precipitate the copper-phase late in the solidification process and hinder the feeding process to make sound castings. As a result, the copper-containing hypereutectic Al-Si alloys that have been used in the past as parent bore materials have been compromises of low silicon content, which has translated into low wear resistances and the need for special surface treatments.

This paper presents the new advancements to the old hypereutectic aluminum-silicon technology for linerless parent bore aluminum blocks. The technology is centered around the use of a copper-free hypereutectic aluminum-silicon alloy parent bore material and a piston coating that has particles of a solid lubricant embedded in the plated coating. Because there are no commercially available copper-free hypereutectic aluminum-silicon alloys, this paper contains the thermal/physical/mechanical data for such alloys.

INTRODUCTION

The inherent advantages of lighter weight and better heat transfer that aluminum (and more specifically hypereutectic Al-Si alloys) can economically provide for engine blocks have long been recognized.

These advantages of lighter weight and better heat transfer, regardless of their desirability in engine design and performance, have until recently proven insufficient justification for acceptance of aluminum engines by the U.S. automotive industry manufacturers. The situation has clearly changed as each of the American automotive manufacturers has a series of aluminum engine blocks currently in production. Amongst these include the following engines: GM's lost Foam Cast Saturn, ZR-1 Corvette, Aurora and Northstar engines; Ford's 4.6L Continental, 2.5L Contour/Mystique/Mondeo, 3.0L Taurus/Sable and 3.9L Lincoln Sedan engines: and Chrysler's Viper engine along with the series of 2.7L, 3.2L and 3.5L V-6 designs that support their full-size LH cars. All of these aluminum engines rely upon use of iron liners and suffer the inherent weight, thermal conductivity and thermal expansions-based disadvantages commonly associated with their use.

General Motors was clearly the technological leader in the early 1970's when they introduced the all aluminum Vega block using 390 Alloy Technology. Twenty-five years later, still using similar technology, Germany is the leading producer of the all-aluminum performance blocks (by Porsche, Daimler-Benz and BMW).

Specifically, Daimler-Benz's usage of high silicon-aluminum sprayed and extruded liners coupled with the Porsche Boxster engine's use of Loka-sil technology represent innovative technologies that provide further evidence of the performance-based value that the category of hypereutectic aluminum engines/cylinders can bring the automotive arena.

Conversely, US automotive manufacturers are still without an all-aluminum block in production. This state of affairs may change because the Japanese automotive manufacturers have a stated goal of decreasing the weight of the automobile by 40%. Thus, the cast iron block and the aluminum block with cast iron liners, both will be unacceptable in the relatively near future for automakers that are interested in gaining or maintaining market share.

Recognizing the undisputed importance of maximizing efficiency of deployment of our scarce fossil fuels and preservation of our global environment (CAFÉ standards, emissions requirements, USAMP / USCAR initiatives / consortium, etc.), this paper will seek to expand upon the positive application of the category of high silicon aluminum based automotive engines demonstrated to date by offering a lower cost, more robust, manufacturing-feasible approach borne out of a marine engine regime that makes possible widespread application of all aluminum based engines for the automotive industry.

MAIN SECTION

BACKGROUND

In the mid-1980's, Mercury Marine started its largest and most systematic field study in its die cast Merc 25 block to evaluate a family of copper-free hypereutectic aluminum-silicon alloys called Mercosil technology. Mercosil is an acronym for Materials Engineered for Resistance: Corrosion (copper free) and Wear (silicon). After accumulating 1,000,000 field hours with test fleet of engines with no failures attributed to the alloy, the decision was made to go into full production in 1994 with Mercosil for the Merc 25 block.

The Mercosil Merc 25 engine replaced a very successful engine block that had chrome plated bores, and was in production for over 20 years. The only flaw inherent in the previous Merc 25 with chrome plate bores (besides cost of manufacture) was its susceptibility to fatal damage when large debris was ingested by the engine. The Mercosil Merc 25 is tolerant of ingested debris

Mercosil engine has a clear advantage because low emission 2-cycle engines that have to conduct heat out of the combustion chamber through a cast iron liner will be penalized in performance and durability over the all-aluminum Mercosil engine that has a high conductivity path for the combustion heat.

The desirability and basis to convert engines that currently rely upon the combination of cast iron liners fit into hypoeutectic aluminum blocks also applies to the automotive community. This is particularly true as the pressures to simultaneously reduce emissions while improving performance continue to mount. Usage of all-aluminum Mercosil provides performance-based benefits (reduced weight, improve thermal conductivity, greater rigidity) without the drawbacks typically associated with manufacture of typical copper containing hypereutectic aluminum alloys.

Mating Material Combinations

Piston Coating

In the case of copper-free hypereutectic aluminum alloy-based engine blocks, the choice of piston surface modification has been found to be important as it can and should serve as much more than simply a generic barrier coating.

The recommended piston coating is an electroplated nickel ceramic coating. Phosphorous is present in the coating as a hardening agent along with hexagonal boron nitride as dispersed ceramic particles encapsulated within the coated film.

Results during 400 hour engine endurance testing revealed power output of the engine to be generally higher over the entire operating range of the engine. Maximum increases of 6.8% occurred at the lowest engine speeds (2500 rpm) with approximately 1% improvements occurring at 6000 rpm.

These above stated results are interpreted as being attributable to the combination of properties that this piston surface modification technology exhibits.

In addition to this high level of compatibility with the hypereutectic aluminum cylinder bore and high hardness, properties of NCC coating are characterized by high levels of corrosion, scuff and wear resistance along with low frictional coefficients derived from the presence of boron nitride particles. Projected expansion of Mercosil technology into hotter running low emissions engines are expected to yield protection from ring groove microwelding.

The following three diagrams in Figure 1A, 1B, and 1C illustrate hardness, wear and frictional properties for both the Boron Nitride and Silicon Carbide-containing versions of nickel ceramic composite coatings.

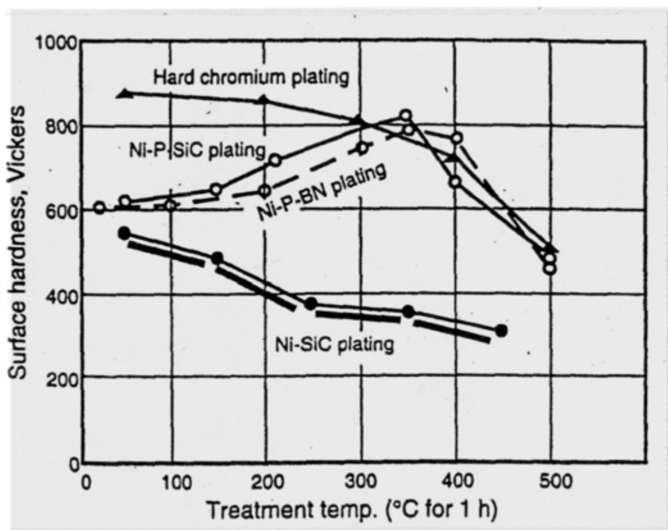

Figure 1A. Hardness of NCC, Ni-SiC, and hard Chrome plating as a function of high temperature exposure.

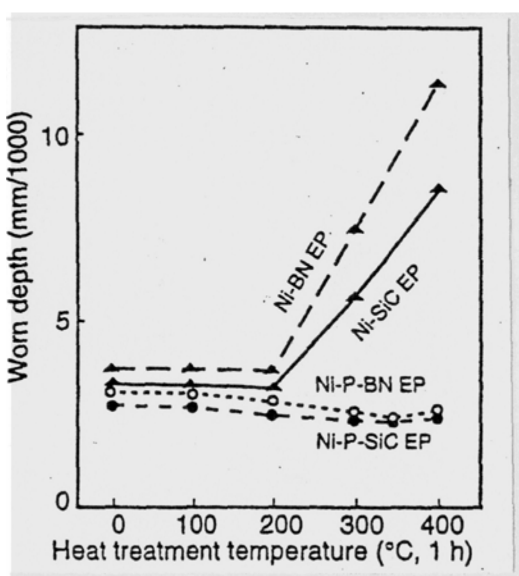

Figure 1B. Impact of phosphorus on wear properties of nickel based coatings. (Ultra high pressure wear tester, block & ring Cr plated cast iron, 1h.)

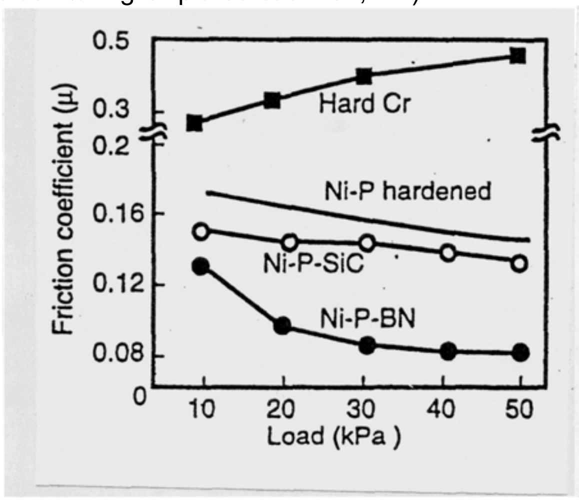

Figure 1C. Comparison of surface friction coefficients (rigid ball – 52100 type)

Piston Rings

The top piston ring should preferably be a martensitic hardened cast iron such as Goetze F-14 ring. A chrome-plated ring is also considered acceptable but a nitrided ring is less desirable. Internal engine testing evaluations by Mercury have documented improved piston ring sealing against a Mercosil cylinder bore thus contributing towards both reduced emissions and increased power.

Cylinder Bore and Surface Finish

Based on six years of production experience, honing is not necessary for the Mercosil 2-cycle application with a thermostat when TCW-3 oil is used with a regular unleaded gasoline. Diamond boring Mercosil to a 20 microns RA max. surface finish is sufficient. In this two-cycle application, the thermostat insures that condensation on the bore surfaces will not occur while the TCW-3 oil insures that oil of good film strength is being used. The absence for the need to hone a pattern into the bore is significant because it is the general practice to hone a pattern into the bore to hold the lubricant. However after 1000 hours of running the "as bored" surface, it has the topography of a honed and etched bore.

Significantly, when the as-bored Mercosil bore is honed and Osborn brushed, the Mercosil bore outperforms the chrome plated bore in the 30% kerosene test and the 4-Stroke oil test.

PRODUCTION AND EXPERIMENTAL USE OF MERCOSIL

The following production and experimental uses of Mercosil were documented before the production commitment to a linerless Mercosil engine block was made.

- The Mercosil die-cast bearing carrier spool replaced an anodized Al-alloy 360 die-cast. In the bearing carrier spool application Mercosil had to have ductility greater than 1%, high cycle fatigue strength of 89.63MPa (which was 50% higher than Al-alloy 360), wear resistance and brinelling resistance greater than that of the anodized Al-alloy 360.

- Mercury Marine tested the linerless Mercosil version of the V-6 200 hp block. The technical results revealed 6% greater horsepower (i.e., greater than 212 hp) during break-in than the production chrome plated bored blocks.

- Mercosil die cast blocks, for the in-line 4-cylinder engine family, that covers the 100 to 120 horsepower range, was also tested with cast iron liners. The Mercosil engine ran 300 hours of dock endurance with no failure while aluminum alloy 360 engine was sticking pistons within 100 hours, due to heat distortion caused by hot exhaust at the upper bore area. The positive results were attributed to Mercosil higher modulus and lower thermal expansion coefficient than aluminum alloy 360.

- Mercosil has been successfully evaluated in a linerless compressor. The linerless Mercosil compressor outperformed the cast iron linered version that was more costly to manufacture. The temperatures of the Mercosil bore surface and piston dome are estimated to be running 38°C cooler than the air compressor with the cast iron liner. These temperature estimates for the Mercosil bore surface and piston dome are deduced from adiabatic calculations from air out temperature measurements at the head. The increased life of the crankpin bearing was also attributed to the Mercosil design. The heat transmitted down the connecting rod to the crankpin bearing adversely affects the life of the crankpin bearing. In the cast iron linered compressor, the crankpin bearing exhibits a bluing after 200 hours of running and needs to be replaced after 350 hours. In the all-aluminum Mercosil compressor the bearings are perfectly serviceable, with no bluing after 400 hours.

- Cagiva group has provided 4-stroke cylinder engine validation for Mercosil in its highest performance test engines, and has Mercosil under development with automotive companies in Europe. Mercury Marine's own 4-stroke cycle engine has been successfully run as a linerless Mercosil block in several 300 hour dock endurance tests at wide open throttle. Both of these development programs utilized nickel ceramic composite coated (NCC Coat) pistons. The Cagiva validation of Mercosil in their highest performance Husqvarna engine for 4-stroke cycle engines is presented below. In the 95 HP/liter engine the Mercosil engine at any RPM exhibited approximately 6% or more horsepower than the honed NIKASIL plated bore (which used graphite-coated pistons and special plated rings) as illustrated in figure 2. Even more dramatic is the significant lower blow-by that was exhibited by the Mercosil engine (see figure 3). The explanation for these improved results for Mercosil is because the rings seat into the Mercosil bore faster and better than the rings seat into the NIKASIL bore and this results in lower blow-by and (in conjunction with the benefits yielded for NCC Coated pistons) increased horsepower.

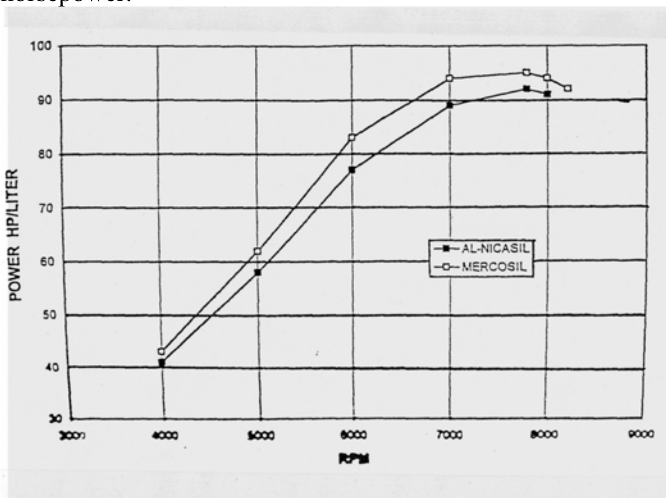

Figure 2. Husqvarna Engine – HVA 610 TC after 4 hours

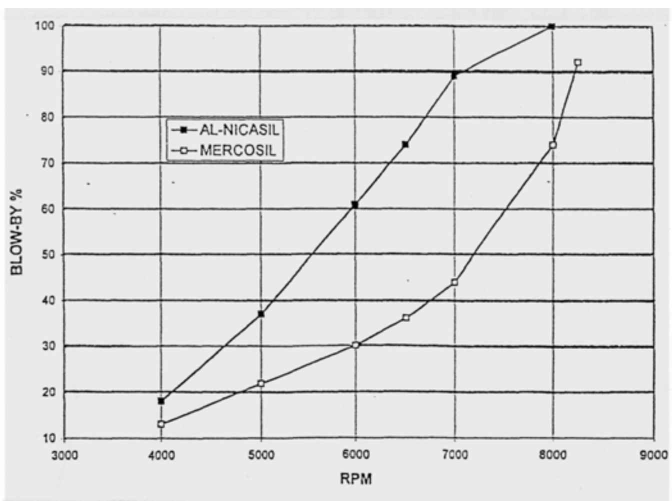

Figure 3. Husqvarna Engine- HVA 610 TC after 4 hours

PHYSICAL AND MECHANICAL DATA FOR THE DESIGN USE OF MERCOSIL

Compositions for Mercosil.

The copper-free hypereutectic Al-Si alloys in this paper represent improvement over the existing 390 Al-alloy technologies, which has:

1. Limited feeding characteristics due to copper phase precipitation late in the solidification process and silicon micro segregation. Compared to 390, the narrow solidification range of Mercosil inherently yield a more uniform distribution of primary silicon and makes sound castings easier to produce, particularly in a slow cooling rate process such as Lost Foam.
2. Limited salt water corrosion resistance (due to its 4.5% copper content);
3. Limited wear resistance (because the already large solidification range does not allow, in a practical sense, the option of increasing the silicon content).

Mercosil family of alloys removes these limitations and represents an improvement over the existing 390 technologies. The narrow solidification range of Mercosil is considered fundamentally important and unique, especially for micro porosity-free soundness and for the lost foam casting process.

Three alloy compositions have been identified in Table 1 as having potential. Mercosil is represented by the 17 – 19% Si range in Alloy 1 and is characterized by the lowest solidification range. Alloy 2A represent a 19 – 22% Si range that has an acceptable liquiding for die casting, which must always be concerned about die life, and Alloy 2B has a 22 – 25% Si range for higher temperature die casting and other casting processes. In all of these alloys particular thought has been given to the silicon composition range as it might affect the machining plant. To that end, a quantity called the microstructure variability has been defined which should correlate with the machining variability that a machining plant might experience.

For a given composition range specification in silicon, the largest variation in the primary silicon volume fraction that can result from the composition limits is the microstructure variability and this is defined as:

$$\frac{\text{Volume Fraction Primary Silicon @ upper end of composition} - \text{Volume Fraction Primary Silicon @ lower end of composition}}{\text{Volume Fraction Primary Silicon @ lower end of composition range}}$$

Where the volume fraction of primary silicon at each extreme, is given by the following:

$$\text{Volume fraction primary silicon} = \frac{X_{si} - 12}{87}$$

This "machining variability" parameter is defined as the *microstructure variability*. For Mercosil Alloy 1 (17-19% Si) it is 40%; while for Mercosil Alloy 2A (19-22% Si) and Mercosil Alloy 2B (22-25% Si) it is 44% and 30% respectively. All these values are lower (i.e. better) than Al-alloy 390, which has a microstructure variability of 50%. It is noteworthy to point out that the highest silicon Mercosil (22-25% Si), with twice the volume fraction of primary silicon as Mercosil Alloy 1, should exhibit 33% less variability (or 33% more consistency) than Mercosil Alloy 1. Predictability can relate to machining plant acceptability (i.e., more consistency at higher hardness levels is sometimes preferred over less consistency at lower hardness levels).

Table 1: Mercosil Compositions: Alloy 1, Alloy 2A, Alloy 2B

Chemical Composition of Allowed Limits

	Residual Elements
Copper	0.25 max
Manganese	0.30 max
Zinc	0.10 max
Titanium	0.20 max
Others – each	0.10 max
Others – total	0.20 max
Aluminum	Remainder

Alloy 1: Mercosil (Microstructure Variability = 40%)

Mfg. Process	Silicon	Iron	Magnesium
Die casting	17.0-19.0	1.20 max	0.4-0.7
Perm mold	17.0-19.0	0.60 max	0.4-0.7
Sand	17.0-19.0	0.25 max	0.4-0.7
Lost Foam	17.0-19.0	0.25 max	1.0-1.5

Alloy 2A:

(Microstructure Variability = 44%)

Mfg. Process	Silicon	Iron	Magnesium
Die casting	19.0-22.0	1.00 max	0.7-1.3
Perm mold	19.0-22.0	0.60 max	0.7-1.3
Sand	19.0-22.0	0.25 max	0.7-1.3
Lost Foam	19.0-22.0	0.25 max	1.0-1.5

Alloy 2B:

(Microstructure Variability = 30%)

Mfg. Process	Silicon	Iron	Magnesium
Die casting	22.0-25.0	1.00 max	0.7-1.3
Perm mold	22.0-25.0	0.60 max	0.7-1.3
Sand	22.0-25.0	0.25 max	0.7-1.3
Lost Foam	22.0-25.0	0.25 max	1.0-1.5

The volume fraction of primary silicon in the microstructure varies linearly with the silicon content above the eutectic composition, according to the following:

$$\text{Volume fraction primary silicon} = \frac{X_{si} - 12}{87}$$

For a given composition range in silicon, a measure of the largest variation in the primary silicon volume fraction might be expected in a machining plant is:

$$\frac{(\text{Vol Fraction Primary Silicon @ upper end of composition range}) - (\text{Vol Fraction Primary Silicon @ lower end of composition range})}{\text{Vol Fraction Primary Silicon @ lower end of composition range}}$$

This quality is defined as the Microstructure Variability, and should be a parameter correlatable with the machining difficulties at a given silicon level.

ULTIMATE TENSILE STRENGTH AND YIELD STRENGTH.

The standard machined properties are listed in Table 2. It should be emphasized that the UTS depends on the primary silicon particle size. Large particle size is bad; small particle size is good. The typical values in Table 2 assume proper refinement of the primary silicon.

Table 2:

Typical experimental minimums for mechanical properties of separately cast test bars for Mercosil and Super Mercosil.

Alloy 1: Mercosil

Temper	Casting Method	Tensile Strength MPa min.	Yield Strength MPa min.	Elongation (%) min.
F	Die cast	243	209	1.0
	Perm mold	167	153	1.0
	Sand/foam	139	125	1.0
T5	Die cast	264	229	1.0
	Perm mold	167	153	1.0
	Sand/foam	139	125	1.0
T6	Perm mold	271	257	1.2
	Sand/foam	209	195	1.0
T7	Perm mold	236	222	1.0
	Sand/foam	209	195	1.0

Alloy 2A and 2B: Super Mercosil

Temper	Casting Method	Tensile Strength MPa min.	Yield Strength MPa min.	Elongation (%) min.
F	Die cast	215	215	0.5
	Perm mold	160	160	0.5
	Sand/foam	139	139	0.5
T5	Die cast	236	236	0.5
	Perm mold	160	160	0.5
	Sand/foam	139	139	0.5
T6	Perm mold	257	257	0.5
	Sand/foam	229	229	0.5
T7	Perm mold	222	222	0.5
	Sand/foam	181	181	0.5

MODULUS OF ELASTICITY AND THERMAL COEFFICIENT OF EXPANSION.

The modulus of elasticity and the thermal coefficient of expansion vary linearly with silicon content because the Al-Si alloys are two-phase alloys over the composition range. The modulus of elasticity increases with increasing silicon content and is 86.9 GPa at 19% silicon, which is 25% stiffer than pure aluminum and 15-20% stiffer than most hypoeutectic Al-Si alloys as demonstrated in figure 4. In contrast, the thermal coefficient of expansion decreases with increasing silicon content, which is one of the reasons why pistons are made out of hypereutectic Al-Si alloys of 20% silicon or more. At 20% Si the thermal coefficient of expansion is 17.5 x 10-6/C, which is 23% lower than the thermal coefficient of expansion of hypoeutectic Al-Si alloy 356, which contains 7% silicon (see figure 5). In combination, both of these physical properties contribute to the improved bore distortion resistance of the 2-stroke cycle engine block, which, by design, non-uniformly heat loads the bore by directing a hot exhaust at one side of the upper bore and expects the bore to stay round.

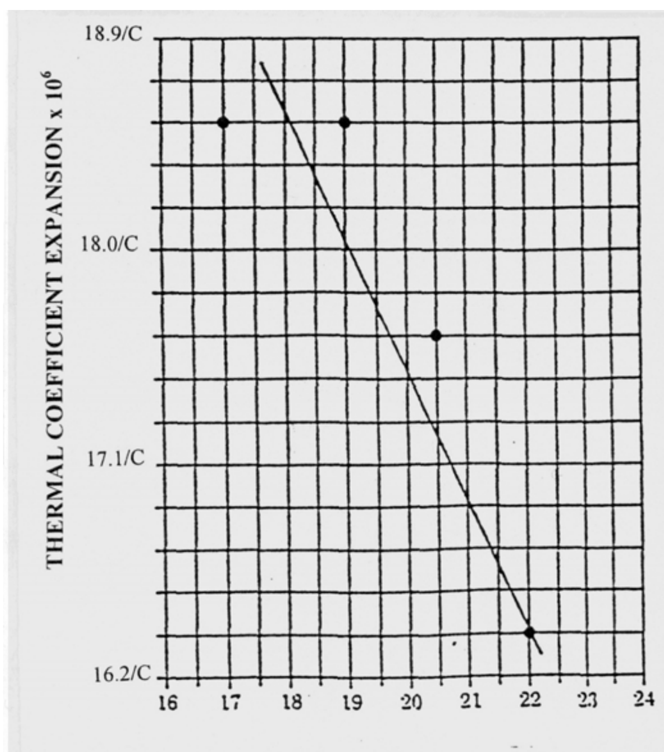

Figure 4. Mercosil thermal coefficient of expansion vs. temperature

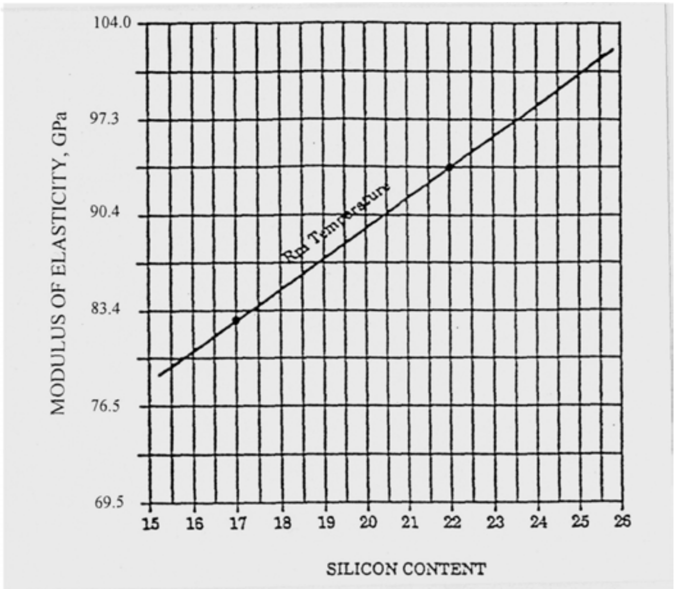

Figure 5. Modulus of Elasticity.

FATIGUE PROPERTIES.

The fatigue properties of hypoeutectic Al-Si alloys are quite accurately represented in the linear plot of log (stress) vs. log (number of cycles) for the Rs-1 loading condition. On such a diagram, the value of the stress where failure occurs in 10 million cycles can conveniently be defined as the high cycle fatigue strength of the material. Based on the data contained in the figure 6 below, the high cycle fatigue strength of hypoeutectic Al-Si alloy, as defined above, is approximately 59 MPa ± 3.5 MPa, irrespective of the heat treatment of the alloy.

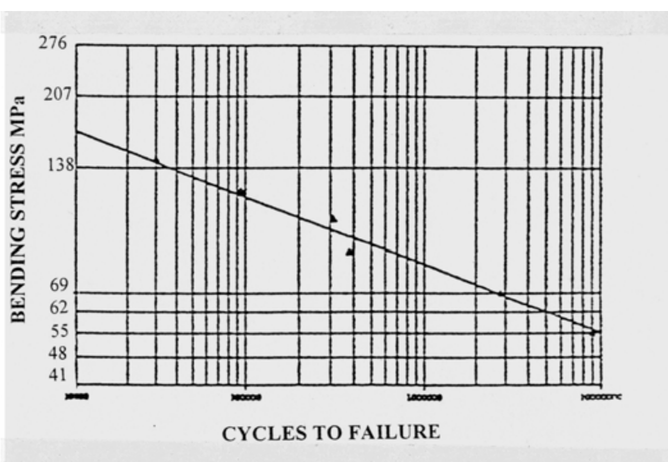

Figure 6. 319T5 Aluminum Alloy.

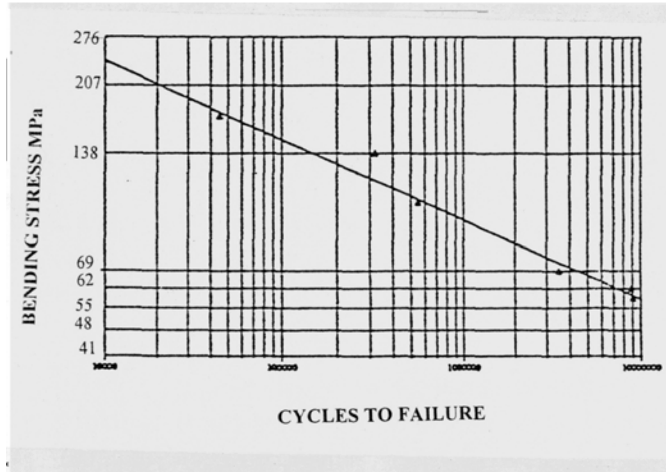

Figure 7. 356T6 Aluminum Alloy.

This concept that the fatigue strength (at 10 million cycles) is not dependent on the ultimate tensile strength of the alloy is quite unlike the case for steels, where the fatigue strength markedly depends on the ultimate tensile strength of the alloy. For hypoeutectic Al-Si alloys, a high ultimate strength material (see figure 7), i.e. one which has been put in a T6 heat treatment condition, is characterized by a steeper downward slope in the low cycle region of the failure stress vs. log (number of cycles) plot, than a low ultimate strength material, i.e. one which has been put in a T5 heat treated condition. However, in both the high UTS case and the low UTS case, the two fatigue curves cross the 10 million cycle mark at approximately the same failure stress value of 59 ± 3.5MPa. Material type, i.e. whether the alloy is 356 or 319, does not significantly change the high cycle fatigue strength determined from the failure stress vs. log (number of cycles) curve.

In contrast to the hypoeutectic Al-Si alloy that do not exhibit an endurance limit, at least down to 41 MPa, hypereutectic Al-Si alloy clearly exhibits an endurance limit at approximately 90 MPa as shown in figure 8. As a result, hypereutectic Al-Si alloys have high cycle fatigue strength 50% higher than that of hypoeutectic Al-Si alloys.

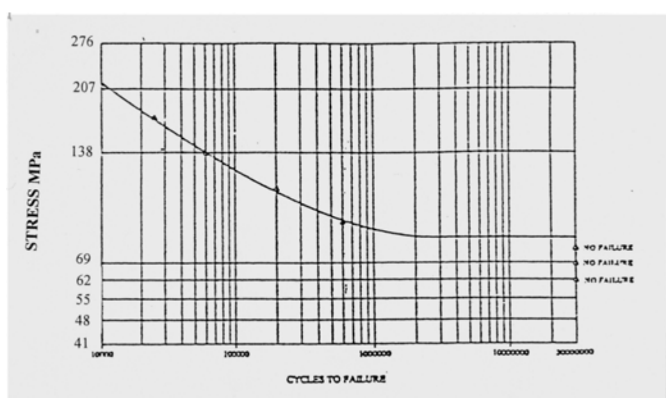

Figure 8. Mercosil Alloy

FRACTURE TOUGHNESS.

The fracture toughness value of a material (*in* $MPa\sqrt{m}$) for a sheet specimen with a through-thickness crack of length, a (in meters) is given by the expression

$$K_{Ic} = \sigma \sqrt{\pi a}$$

Where σ is the stress, in MPa, and has a value less than the yield strength of the material. Another way of stating the fracture toughness concept is as follows: The critical value (identified by the subscript "c") of the stress intensity factor "K" for perpendicular loading mode (identified by the "I" subscript) is the fracture toughness of the material and represents that critical value where an infinitely shaped crack will unstably grow under the application of elastic stress σ less than the yield stress. The replacement maintenance milestone of the aluminum sheet skins on airplanes are scheduled so that the largest allowable flaw detectable, a max. is matched with the highest allowable elastic stress, σ max., such that the calculated stress intensity factor K_I is less than the fracture toughness of the material.

In practice the fracture toughness of the material can be obtained from crack growth curves, where the incremental crack growth length per cycle, i.e. $\Delta a / \Delta N$, is plotted against the stress intensity factor K_I. The value of the stress intensity factor where the crack growth rate becomes infinite is the fracture toughness, K_{Ic}, of the material. This K_{Ic} value can be obtained visually from the curves below. The figure 9 (and figure 10, from Kobayashi, Ninomi, Hirota and Egashira, in Science and Engineering of Light Metals, Rasolm 191, conference, Tokyo, Japan, October 1991) shows the crack growth curves for a series of aluminum – silicon alloys.

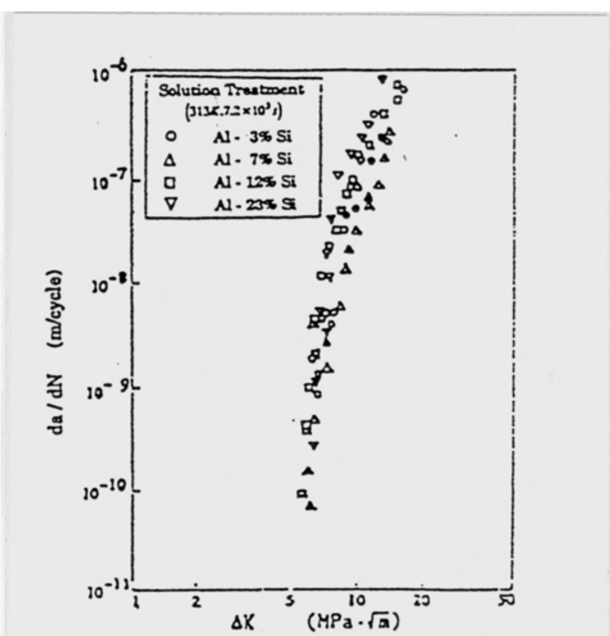

Figure 9. Relationships between da/dN and ΔK in high purity Al-Si binary alloys.

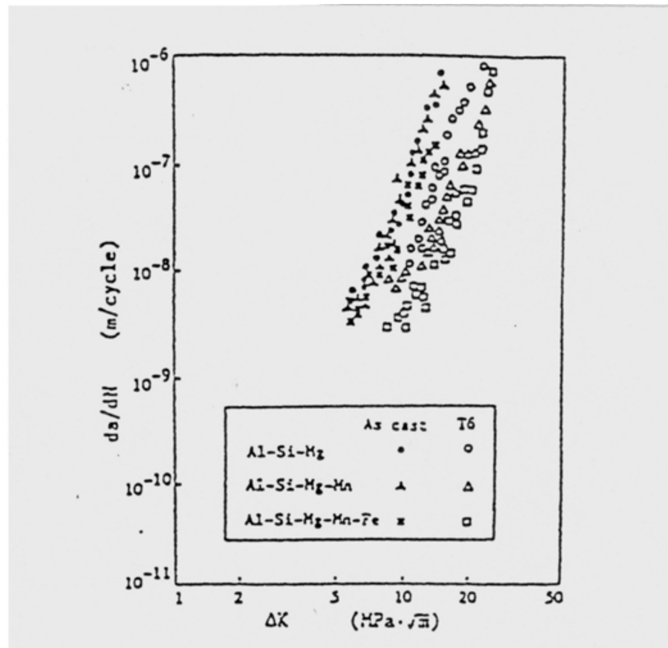

Figure 10. Relationships between da/dN and ΔK in high purity Al-Si-Mg alloys.

These results indicate that high silicon content alloys are associated with lower fracture toughness but the difference between the fracture toughness of the low silicon alloys and of the high silicon alloys is small. In essence, the fracture toughness of hypereutectic Al-Si alloys in the as cast condition is approximately 15 $MPa\sqrt{m}$. However, the alloys in the T6 heat-treated conditions have a significantly higher fracture toughness of approximately 30 $MPa\sqrt{m}$. This doubling of the fracture toughness is clearly the reason why casting alloys that are used for structural purposes should be given a T6 heat treatment. Numerical calculations with the fracture toughness equation $K_{Ic} = \sigma \sqrt{\pi a}$ can be used to calculate the critical sized flaw that is unsafe in castings. In the as cast condition, which is associated with a fracture toughness of 15 $MPa\sqrt{m}$, an applied stress of 200 MPa (i.e. a value less than the yield stress) causes unstable growth of a casting flaw a = 1.7mm, according to

$$a = \frac{K_{Ic}}{\Sigma^2\pi} = \frac{(15)^2}{(200)^2} = 0017$$

The works of others on the fracture toughness of Al-Si alloys indicate in a similar manner, that the as cast fracture toughness increases both with decreasing silicon and iron content. These results are shown in figure 11. The data again demonstrates the fracture toughness dependence on silicon content is not strongly dependent on the silicon content if the iron content is 0.32% Fe or higher. This data clearly indicates that the iron phase with the needle-like morphology is particularly detrimental to fracture toughness if the structure is slow cooled. The worst-case fracture toughness values in the figure are the range of 15-20 $MPa\sqrt{m}$ and the best-case fracture values are approximately 30 $MPa\sqrt{m}$. These results are consistent with the previous Japanese results and give the design engineer the conservative value of 15 $MPa\sqrt{m}$ for the fracture toughness of hypereutectic Al-Si alloys.

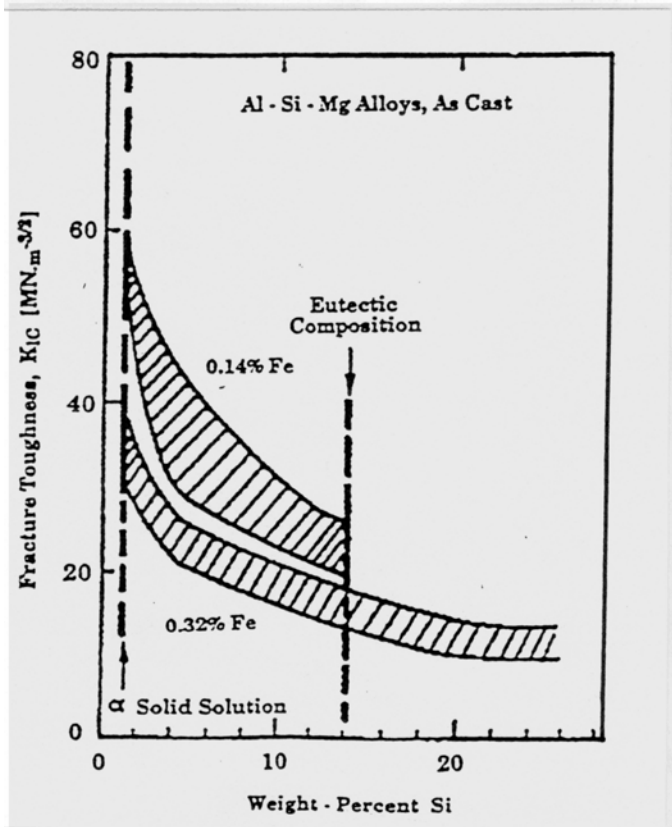

Figure 11. Effect of silicon contents on fracture toughness of two series of Al-Si-Mg alloys.

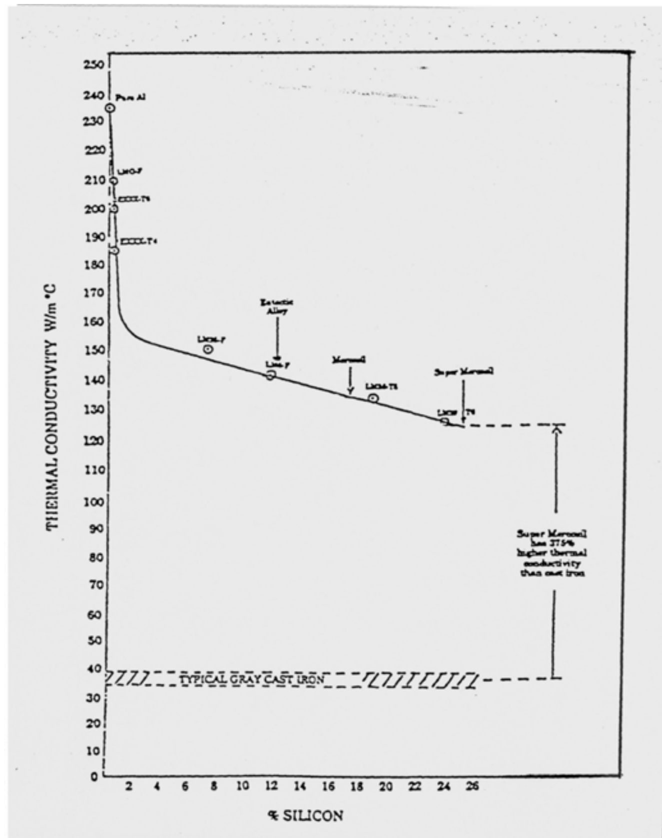

Figure 12. Thermal Conductivity of Aluminum – Silicon alloys with Cast Iron as a reference.

THERMAL CONDUCTIVITY OF ALUMINUM – SILICON ALLOYS.

The thermal conductivity of hypereutectic Al-Si alloys is nearly 400% higher than that of cast iron. This high thermal conductivity is one of the most useful and important properties these alloys have that titanium alloys do not have. Figure 12 shows the variation of thermal conductivity of Al-Si alloys with silicon content. Pure aluminum has a thermal conductivity of approximately 235 W/*m°C* This value drops dramatically to 160 W/*m°C* at the maximum solubility of silicon in aluminum (which is 1.65%). Above 1.65% Si, the decrease in the thermal conductivity with increasing silicon content is linear and comparatively low, reaching a value of 135W/*m°C* at approximately 19% silicon. The reason for the linear variation of the thermal conductivity with increasing silicon content above 1.65% Si is because the microstructure of these alloys are just mechanical mixtures of the two phases in the structure, an aluminum phase (that can hold 1.65% in Si in solution at 577ºC) and a pure silicon phase. The effect of dissolving copper in aluminum is to lower the thermal conductivity of aluminum. Thus, higher thermal conductivities for copper-free Al-Si alloys are expected.

In fact the effect of heat treatment on thermal conductivity is best appreciated by understanding the effect that dissolving any element in aluminum is to lower its thermal conductivity. Thus the solution treated and quenched condition is expected to yield the lowest thermal conductivity for any silicon concentration. Die-casting approaches this 'maximum dissolved" state. As more precipitation occurs, as it does in going from the T6 heat treatment to the T7 and T5 heat treatments, the thermal conductivity increases. For a typical 7 – 8% silicon-containing alloy, the die casting typically has a thermal conductivity of approximately 96 W/mK whereas values exposed to T6, T7 and T5 heat treatments are characterized by thermal conductivity values of 151 W/mK, 160 W/mK and 167 W/mK, respectively.

CONCLUSION

Based on the data and experiences contained in the body of this paper, it is concluded that in comparison to aluminum engine blocks using iron liners as well as traditional (copper-containing) hypereutectic aluminum alloys, copper-free hypereutectic aluminum-silicon alloys of 18% silicon and above, offer the following performance advantages:

- Higher high cycle fatigue strength;
- Higher wear resistance;
- Better bore distortion resistance (due to lower thermal expansion coefficient and higher stiffness modules),
- Lighter weight;
- Better heat transfer;

Manufacturing advantages include:

- Lower manufacturing costs
- Higher casting soundness
- Improved machinability and tool life

The thermal and physical properties of the copper-free aluminum silicon hypereutectic alloys are closely related to and dependent on the silicon content of the alloy. For example, with increasing silicon content the coefficient of thermal expansion decreases linearly, and the modules of elasticity increases linearly.

Besides having an endurance limit that hypoeutectic aluminum-silicon alloys do not have, the high cycle fatigue strength of hypereutectic aluminum-silicon alloys is 50% higher than that of hypoeutectic aluminum-silicon alloys and is not dependent on the heat treat condition of the alloy, but is dependent on the porosity level.

Heat-treating is important for fracture toughness and thermal conductivity for different reasons. Solution treating temperatures, by enhancing diffusion, round the sharp topography features of interdendritic shrinkage porosity (i.e., blunts the crack tip of the flaw) and therefore increase the fracture toughness. Whereas solution treating temperatures also provide the means for solute elements to dissolve in the base aluminum and thus disrupt the periodicity of the lattice which lowers the thermal conductivity after being quenched to room temperature.

Finally, wear resistance is provided by the volume fraction of primary silicon particles in the microstructure. There is nearly a doubling of the wear resistance in going from the 16% silicon content to the 20% silicon content because the volume fraction of primary silicon doubles with this composition changes.

The exposed primary silicon on the bore surface is thus of paramount importance because it is the mating wear couple with the rings and/or piston coating. Boron nitride particles in the nickel-phosphorous-based piston coating provide an extra low friction surface that enhances the compatibility match in the wear couple that barrier coatings on pistons could not provide heretofore.

Mechanical brushing represents a preferred cylinder bore finishing alternative to etching to remove smeared aluminum and expose rounded edged primary silicon particles that are less abrasive to piston rings.

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