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Friction and Wear of Aluminum-Silicon Alloys

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ALUMINUM-SILICON ALLOYS are noted for their unique combination of desirable characteristics, including excellent castability and low density combined with good mechanical properties. Interestingly, there is no mention of wear resistance in the many published tabulations of the attributes of this class of alloys (see, for example, Ref 1 and 2). In a comprehensive review of the wear characteristics of aluminum alloys, Eyre (Ref 3) remarks on the dearth of published information about the wear resistance of aluminum-silicon alloys, while acknowledging their increased application in environments demanding this physical characteristic.

In the late 1950s, die cast aluminum-silicon alloy cylinder blocks were manufactured for the automotive industry to take advantage of the light weight and good thermal conductivity offered by hypoeutectic alloys such as A356 and A380 (Ref 4). However, because these alloys exhibited only modest wear resistance, the early engine blocks (for example, those produced for the American Motors Corporation Rambler) had a cast-in steel cylinder liner. In Europe, automotive engine blocks were also being die cast in aluminum-silicon alloys (such as LM24 and LM26), but these blocks had liners that were shrink-fitted in place. A major boost was given to the use of lightweight aluminum alloys in automobiles when the energy crisis in the early 1970s resulted in the government mandating improved fuel consumption in automobiles. Because fuel consumption can be directly related to vehicle weight (Ref 5), the use of aluminum in place of cast iron in engine components became highly desirable. However, the use of die cast aluminum engine blocks with a cast iron cylinder liner proved to be too costly in production, paving the way for the development of hypereutectic aluminum-silicon alloys with greater wear resistance that could be used without liners.

One such alloy that has been developed specifically for its high wear resistance is the hypereutectic aluminum-silicon alloy A390 (A390.0), which has been used in engine blocks without a liner. An electrochemical surface treatment is used to etch away some of the matrix aluminum so that the eutectic and primary silicon particles provide the bearing surface, resulting in improved wear resistance. Jorstad (Ref 6) has suggested the use of this alloy for other weight-saving applications where good wear resistance is required (for example, brake drums and disk brake rotors).

A powder metallurgy (P/M) production route for the manufacture of cylinder liners from hypereutectic aluminum-silicon alloys has also been explored (Ref 4). Using this method, the size of the primary silicon particles may be optimized and solid graphite can be added to the matrix to serve as a lubricant. The liners are then inserted into the engine block, which is produced from conventional aluminum-base alloys.

While applications for aluminum-silicon alloys are currently centered in the automotive industry (which accounts for greater than 50% of the market), other applications in communications equipment, instrumentation, and small engines appear likely. The hypereutectic alloys are likely to dominate because their wear resistance, combined with low coefficient of thermal expansion (CTE) and fluidity properties, allows thinner wall castings to be manufactured.

Both the Aluminum Association (AA) and the Society of Automotive Engineers (SAE) designations are commonly used to classify aluminum-silicon alloys in the United States.

Metallurgy of Aluminum-Silicon Alloys

Aluminum alloys for wear resistance applications are based on the aluminum-silicon alloy system. This binary system is a simple eutectic alloy system with the eutectic composition at 12.5% Si (Fig 1). Standard alloys, of course, contain a number of alloying ingredients. Selected commercial alloy compositions are shown in Table 1. Table 2 cross references United States aluminum-silicon compositions with compositions of European and Japanese sources.

At room temperature, the hypoeutectic alloys consist of the soft, ductile primary aluminum phase and the very hard, brittle silicon phase associated with eutectic reaction. It is this silicon phase that contributes to the very good wear resistance of these alloys. The silicon phase is diamond cubic with a density of ~2.6 g/cm^3 (0.094 lb/in.^{3}) and a Vickers hardness of approximately 10 GPa (1.5×10^6 psi). Silicon is essentially insoluble in aluminum (Ref 10). Figure 2 illustrates the typical microstructure of a common hypoeutectic alloy, A357.0. Hypereutectic alloys, the most commonly used wear-resistant alloys, contain coarse, angular, primary silicon particles as well as eutectic silicon. These primary silicon particles impart excellent wear resistance to these alloys. A typical microstructure of an unrefined hypereutectic alloy (A390-type) is shown in Fig 3.

Commercial aluminum-silicon alloys (Table 1) generally contain other alloying elements to further enhance or modify the wear resistance or impart additional properties to these alloys.

Iron. The most common alloying element is iron, which can be tolerated up to levels of 1.5 to 2.0% Fe. The presence of iron modifies the silicon phase by introducing several Al-Fe-Si phases. The most common of these are the α and β phases. The α phase has a cubic crystal structure and appears in the microstructure as a "Chinese script" eutectic. The less common β phases

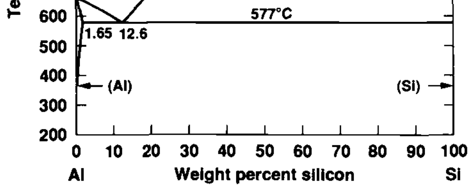


Fig 1 Aluminum-silicon binary phase diagram. Source: Ref 7

Table 1 Nominal compositions of selected commercial alloys recommended for wear applications

	Composition, wt%					
Alloy	Si	Fe	Cu	Mg	Mn	Other
Hypereutectic alloys						
390.0	16–18	1.3	4–5	0.45–0.65	0.1	...
A390.0	16–18	0.5	4–5	0.45–0.65	0.1	...
B390.0	16–18	1.3	4–5	0.45–0.65	0.5	1.5 Zn
392.0	18–20	1.5	0.4–0.8	0.8–1.2	0.2–0.6	0.5 Ni, 0.5 Zn, 0.3 Sn
393.0	21–23	1.3	0.7–1.1	0.7–1.3	0.1	2–2.5 Ni
Eutectic alloys				—		
384.0	10.5–12	1.3	3–4.5	0.1	0.5	0.5 Ni, 3 Zn, 0.35 Sn
336.0	11–13	1.2	0.5–1.5	0.7–1.3	0.35	2–3 Ni, 0.35 Zn
339.0	11–13	1.2	1.5–3	0.5–1.5	0.5	0.5–1.5 Ni, 1 Zn
413.0	11–13	2	1	0.1	0.35	0.5 Ni, 0.5 Zn
4032	11–13.5	1	0.5–1.3	0.8–1.3	...	0.5–1.3 Ni
Hypoeutectic alloys						
319.0	5.5–6.5	1	3–4	0.1	0.5	0.35 Ni, 1 Zn
356.0	6.5–7.5	0.6	0.25	0.2–0.45	0.35	0.35 Zn
364.0	7.5–9.5	1.5	0.2	0.2–0.4	0.1	0.25–0.5 Cr, 0.15 Ni, 0.15 Sn
380.0	7.5–9.5	2	3–4	0.1	0.5	0.5 Ni, 3 Zn, 0.35 Sn
333.0	8–10	1	3–4	0.05–0.5	0.5	0.5 Ni, 1 Zn
332.0	8.5–10.5	1.2	2–4	0.5–1.5	0.5	0.5 Ni, 1 Zn
360.0	9–10	2	0.6	0.4–0.6	0.35	0.5 Ni, 0.5 Zn
383.0	9.5–11.5	1.3	2–3	0.1	0.5	0.3 Ni, 3 Zn, 0.15 Sn

Source: Ref 8, 9

generally appear as needles and/or platelets in the structure. Other iron-bearing phases such as Al_6Fe and $FeAl_3$ can also be found in these alloys. Aluminum-silicon alloys intended for die castings typically have higher minimum iron levels to reduce sticking between the mold and the casting.

Magnesium is added to provide strengthening through precipitation of Mg_2Si in the matrix. In an Al-Fe-Si-Mg alloy, the Al-Si-Fe phases will not be affected by the addition of magnesium. However, magnesium can combine with insoluble aluminum-iron phases, resulting in a loss of strengthening potential (Ref 12).

Copper. The most common aluminum wear-resistant alloys also contain copper. Copper additions impart additional strengthening of the matrix through the aging or precipitation-hardening process ($AlCu_2$ or Q phase) or through modification of the hard, brittle Al-Fe-Si phases by substitution in these intermetallic phases. As the strength of these alloys increases through magnesium and copper additions, some sacrifice in ductility and corrosion resistance occurs.

Table 2 Cross-reference to equivalent wear-resistant aluminum-silicon alloys

Specific composition limits may vary from United States limits.

	Foreign alloy equivalent			
United States alloy	United Kingdom	France	Japan	Germany
390	LM28	A-S18UNG	...	G-AlSi17Cu4
392	...	...	AC9B	...
413	...	...	...	G-AlSi12(Cu)
336	LM13	A-S12UNG	AC8A	...
332	LM26	A-S10UG	AC8C	...
333	LM2	...	AC8B	...
360	...	A-9G	...	G-AlSi10Mg(Cu)
380	LM24	...	...	G-AlSi8Cu3
356	...	A-S7G	AC4C	...

Source: Ref 8, 9

Manganese. Many of the important aluminum-silicon alloys also contain low (<1 wt%), but significant, amounts of manganese. The presence of manganese can reduce the solubility of iron and silicon in aluminum and alter the composition and morphology of the Al-Fe-Si primary constituent phases. For example, manganese additions can favor the formation of constituents such as $Al_{12}(Fe,Mn)_3Si$ rather than the $Al_9Fe_2Si_2$-type constituents. The manganese-bearing constituents are typically less needlelike or platelike than the manganese-free iron- or (iron/silicon)-bearing primary constituents. Manganese additions also improve elevated-temperature properties of the aluminum-silicon alloys.

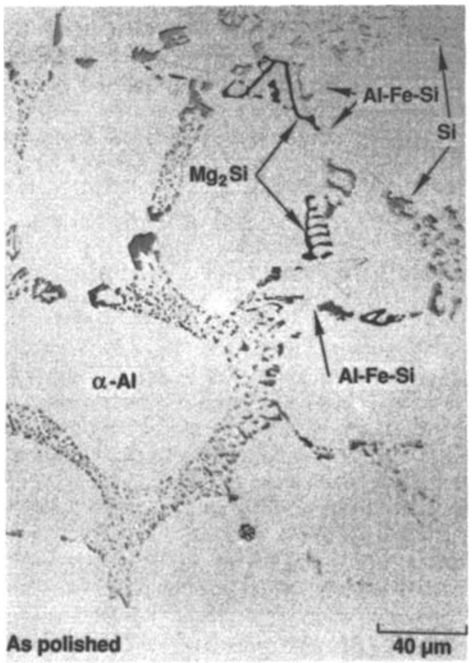


Fig 2 Typical microstructure of type A357.0 hypoeutectic alloy. Source: Ref 11

Cumulative Effect of Alloying Elements. In summary, aluminum wear-resistant alloys are based on alloys containing the hard, brittle silicon phase. Alloying elements such as iron, manganese, and copper increase the volume fraction of the intermetallic silicon-bearing phases, contributing to increased wear resistance compared to binary aluminum-silicon alloys. In addition, magnesium and copper also provide additional strengthening by producing submicroscopic precipitates within the matrix through an age-hardening process.

Properties and Structure

Alloying aluminum with silicon at levels between about 5 and 20% imparts a significant improvement in the casting characteristics relative to other aluminum alloys. As a result, these high-silicon alloys are generally utilized as casting alloys rather than for the manufacture of wrought products. Aluminum-silicon alloys also possess excellent corrosion resistance, machinability, and weldability (Table 3).

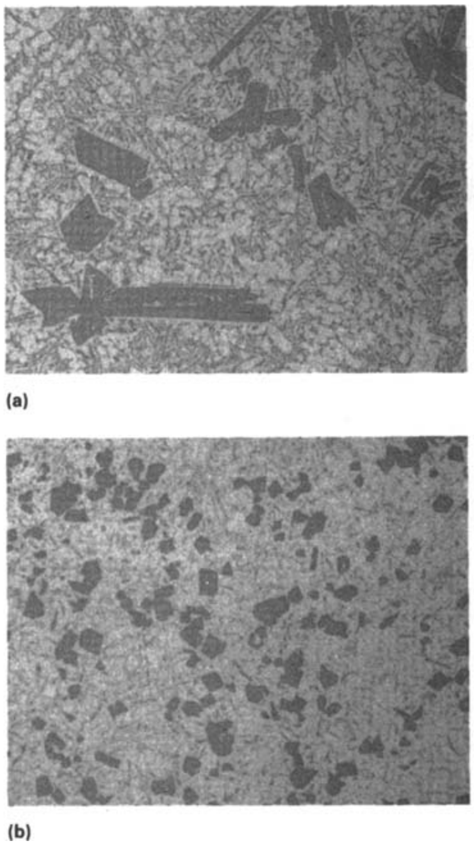


Fig 3 Microstructure of type A390.0 hypereutectic alloy. (a) Unrefined (Graff-Sargent etch). Dark regions contain coarse primary silicon particles in addition to eutectic silica. (b) Refined (as polished). 120×

Table 3 Relative ratings of aluminum-silicon sand casting and permanent mold casting alloys in terms of castability, corrosion-resistance, machinability, and weldability properties

Aluminum Association number of alloy	Property(a)						
	Resistance to hot cracking(b)	Pressure tightness	Fluidity(c)	Shrinkage tendency(d)	Resistance to corrosion(e)	Machinability(f)	Weldability(g)
Sand casting alloys							
319.0	2	2	2	2	3	3	2
354.0	1	1	1	1	3	3	2
355.0	1	1	1	1	3	3	2
A356.0	1	1	1	1	2	3	2
357.0	1	1	1	1	2	3	2
359.0	1	1	1	1	2	3	1
A390.0	3	3	3	3	2	4	2
A443.0	1	1	1	1	2	4	4
444.0	1	1	1	1	2	4	1
Permanent mold casting alloys							
308.0	2	2	2	2	4	3	3
319.0	2	2	2	2	3	3	2
332.0	1	2	1	2	3	4	2
333.0	1	1	2	2	3	3	3
336.0	1	2	2	3	3	4	2
354.0	1	1	1	1	3	3	2
355.0	1	1	1	2	3	3	2
C355.0	1	1	1	2	3	3	2
356.0	1	1	1	1	2	3	2
A356.0	1	1	1	1	2	3	2
357.0	1	1	1	1	2	3	2
A357.0	1	1	1	1	2	3	2
359.0	1	1	1	1	2	3	1
A390.0	2	2	2	3	2	4	2
443.0	1	1	2	1	2	5	1
A444.0	1	1	1	1	2	3	1

(a) For ratings of characteristics, 1 is the best and 5 is the poorest of the alloys listed. Individual alloys may have different ratings for other casting processes. (b) Ability of alloy to withstand stresses from contraction while cooling through hot-short or brittle temperature range. (c) Ability of molten alloy to flow readily in mold and fill thin sections. (d) Decrease in volume accompanying freezing of alloy and measure of amount of compensating feed metal required in form of risers. (e) Based on resistance of alloy in standard salt spray test. (f) Composite rating, based on ease of cutting, chip characteristics, quality of finish, and tool life. In the case of heat-treatable alloys, rating is based on T6 temper. Other tempers, particularly the annealed temper, may have lower ratings. (g) Based on ability of material to be fusion welded with filler rod of same alloy. Source: Ref 13

Binary hypoeutectic alloys are too soft to have a good machinability rating. However, the machinability of aluminum-silicon alloys is generally very good in terms of surface finish and chip characteristics. Tool life can be short with conventional carbide tools, particularly in the case of the hypereutectic alloys. With the recent introduction of diamond cutting tools, tool life has been significantly increased, making the machining of the hypereutectic alloys practical.

Corrosion resistance of these alloys is generally considered excellent. Alloys containing increasing amounts of copper have a somewhat lower corrosion resistance than the copper-free alloys as measured in standard salt spray tests.

Because of their high fluidity and good casting characteristics, these alloys are highly weldable with conventional welding techniques. For joining purposes, brazing alloys and filler wire alloys (for example, alloys 4043 and 4047) (Ref 14) are also based on the aluminum-silicon alloy system.

For wear applications, the important physical properties of these alloys include thermal expansion, thermal conductivity, electrical conductivity, and Young's modulus. Data for these properties are available in standard references (Ref 13-18). Because silicon is generally in precipitate form, the rule of mixtures is applicable when calculating the properties.

Heat Treatment. Depending on the application, thermal treatments can be employed to:

- Increase strength
- Control thermal growth
- Improve ductility

Aluminum-silicon alloys containing copper and magnesium can be heat treated and aged in the same manner as wrought precipitation-hardened alloys. Depending on the strength level required, room-temperature aging (T4 temper) or elevated-temperature aging (<205 °C, or 400 °F) (T6 temper) may be required after heat treatment to obtain the necessary properties. As the strength of the alloy increases from the T4 to T6 temper, reductions in ductility will occur as the strength increases.

In addition, aluminum-silicon and Al-Si-*X* alloys can be given a higher temperature (205 to 260 °C, or 400 to 500 °F) aging treatment from the as-cast condition to improve their strength and thermal stability. This is particularly important for applications where dimensional tolerances are critical (for example, when the alloy is operated at elevated temperatures as a piston component in an engine). Generally, such an aging practice is designated by the T5 temper.

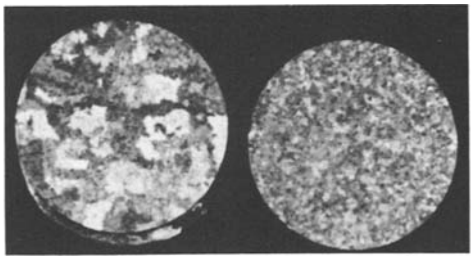
High-temperature (480 to 540 °C, or 900 to 1000 °F) treatments can also be given to aluminum-silicon and Al-Si-*X* alloys to improve their ductility. These thermal treatments modify the angular primary silicon particles to a more rounded shape. This rounded shape reduces the tendency for crack initiation beginning at the sharp edges of the particles. Such treatments are particularly effective on the hypereutectic alloys. Other means of modifying the shape for improved ductility are discussed in the sections "Modification" and "Refinement" in this article.

Principles of Microstructural Control. The three categories of aluminum-silicon alloys are based on the silicon level (Table 1). These alloy categories are hypoeutectic, eutectic, and hypereutectic. The hypoeutectic alloys solidify with α-aluminum as the primary phase followed by aluminum-silicon eutectic. Other solutes (for example, iron, magnesium, and copper) form phases that separate in the freezing range of the alloy in the interdendritic locations (Fig 2).

Hypereutectic alloys solidify in a similar manner, but in these alloys silicon is the primary phase rather than α-aluminum (Fig 3a). The eutectic alloys solidify principally with an aluminum-silicon eutectic structure; either aluminum or silicon is present as a primary phase depending on which side of the eutectic composition (12.7% Si) the alloy lies. A brief description of microstructural control is given below; additional information is available in Ref 2 and 12.

Grain Structure. The grain size of the primary aluminum is controlled through the addition of heterogeneous nuclei to the melt in the form of master alloy inoculants such as Al-6Ti or Al-Ti-B (in the latter, the titanium can range from 3 to 5% and the Ti:B ratio from 3:1 to 25:1). Grain sizes vary from ~100 to 500 μm (~0.004 to 0.020 in.). An example of the effect of grain refinement by an Al-Ti-B refiner is shown in Fig 4.

Cell Size. The interdendritic arm spacing (or cell size) is controlled by the cooling rate (Ref 19), which is in turn a function of the casting process and section thickness. The smallest cell size is achieved with thin-wall high-pressure die casting. At the other extreme, thick-wall sand castings exhibit the largest dendrite cell size. Casting processes such as low-pressure die casting and permanent mold casting provide intermediate solidification rates and consequently cell sizes that lie between the two extremes. In a



(a) (b)

Fig 4 Effect of grain refinement by the addition of an Al-5Ti-0.2B master alloy to type A356.0. (a) Without titanium addition. (b) With 0.04% Ti addition. Etched with Poulton's reagent. 0.85×

similar fashion to the cell size, the constituent phase size is largely controlled by the freezing rate.

Modification. The term modification refers to the change in morphology and spacing of the aluminum-silicon eutectic phase induced by the addition of a chemical agent such as sodium or strontium. There is a change from large divorced silicon particles to a fine coupled aluminum-silicon eutectic structure with an addition of approximately 0.001% Na or 0.005% Sr to the melt. Varying degrees of modification (Fig 5) are obtained with lower levels of addition. For details of the mechanism and practice of modification, see Granger and Elliott (Ref 12).

Antimony is also used to modify (more accurately, refine) the eutectic structure in hypoeutectic and eutectic alloys, particularly in Europe and Japan. Like sodium and strontium, it increases the fluidity of the alloys and improves mechanical properties. Furthermore, it is permanent, allowing melts to be more effectively degassed, which, in turn, provides sounder castings. The great disadvantage of antimony is that it poisons (or negates) the effect of sodium and strontium, and it also creates a problem in recycling. An additional serious drawback is the potential for the formation of stibine gas, which is highly toxic. Unlike sodium and strontium, which can be used to effectively modify eutectic structures over a wide range of freezing rates, antimony provides eutectic refinement only at the relatively high rates experienced in die castings and some thin-wall permanent mold castings.

Refinement. In hypereutectic alloys, the primary phase is silicon. In order to provide the desired small well-dispersed silicon particles, phosphorus is added to the level of about 0.1% P through the addition of a master alloy such as Cu-10P. The phosphorus combines with aluminum to form aluminum phosphide, AlP, which provides effective nuclei for the silicon phase much the same as TiB_2-type particles are effective nuclei for α-aluminum (Fig 3b). However, phosphorus also negates the effectiveness of sodium and strontium. It does so by combining with them to form phosphides, which do not modify the eutectic structure. Similarly, sodium and strontium reduce the effectiveness of phosphorus additions by refining the primary silicon phase.

Gas Porosity. Hydrogen porosity can be controlled by maintaining gas levels at ≤ 0.10 cm^3/100 g. This is not readily accomplished, particularly when modification of the melt is being sought with the addition of sodium or strontium. However, gas fluxing methods are available (Ref 20) that provide the means of reducing hydrogen levels to the desired range.

Also deleterious to casting soundness is the presence of nonmetallic inclusions that act as nuclei for gas pores. Various molten metal filtration systems are available for inclusion removal (Ref 20).

Sludge. A problem experienced with aluminum-silicon alloys is the formation of hard intermetallic phases of the Al(FeM)Si-type, which settle out under gravity from the melt (Fig 6). The conditions that favor the formation of these phases are low holding temperatures (which are often employed in the die-casting industry); a quiescent melt; and relatively high levels of iron, manganese, and chromium. The relative tendency to form sludge in the holding furnace is given by a segregation factor (SF):

$$SF = (\%Fe) + 2\ (\%Mn) + 3\ (\%Cr) \qquad \text{(Eq 1)}$$

The relationship among the segregation factor, holding temperature, and sludging tendency is given for alloy AA 339 and several other aluminum-silicon alloys in Ref 21.

Wear Behavior

The two major types of wear relevant to industrial applications of aluminum-silicon alloys are "abrasive" and "sliding" wear. These have also been identified by Eyre (Ref 3) as the most common types of wear. Wear mechanisms, though, can be thought of as involving more specific descriptions of local processes occurring in the metal and countersurface of the wear system during the wear process. Wear mechanisms are discussed in detail in this Volume in the Sections "Wear by Particles or Fluids," "Wear by Rolling, Sliding, or Impact," and "Chemically Assisted Wear." The purpose of this discussion is to focus on the interaction between microstructure and wear mechanisms. This is important for aluminum-silicon alloys because of the variety of microstructures that can be achieved as the alloys are processed for particular applications. The relative effects of silicon particles, matrix hardness, and intermetallic constituents on the wear resistance of aluminum-silicon alloys are summarized below.

Silicon Particles. Under relatively light load conditions, which are normally associated with low ($<10^{-11}$ m^3/m) losses, wear resistance is not a strong function of silicon content (Ref 22-25). In general, however, silicon additions to aluminum will increase the wear resistance. The principal mechanism appears to be the influence of the hard silicon particles, which lead to higher overall levels of hardness. The fact that the hard silicon particles are surrounded by a softer and relatively tough matrix improves the overall toughness of the material and can contribute to wear resistance by favoring more plastic behavior. The eutectic and hypereutectic silicon alloys, with increased volume fractions of hard primary silicon particles relative to the hypoeutectic alloys, might be expected to have the best wear resistance of the aluminum-silicon alloys. Andrews *et al.* (Ref 26, 27), for example, found that increasing the silicon content in hypereutectic alloys reduced wear. However, binary alloy data (Ref 22, 28) indicate that the hypereutectic alloys are not necessarily the most wear resistant. Clarke and Sarkar (Ref 28) found that there was a relative minimum in wear for binary aluminum-silicon alloys at about the eutectic level, as did Jasim *et al.* (Ref 22), especially at applied pressures <100 kPa (<15 psi). Clarke and

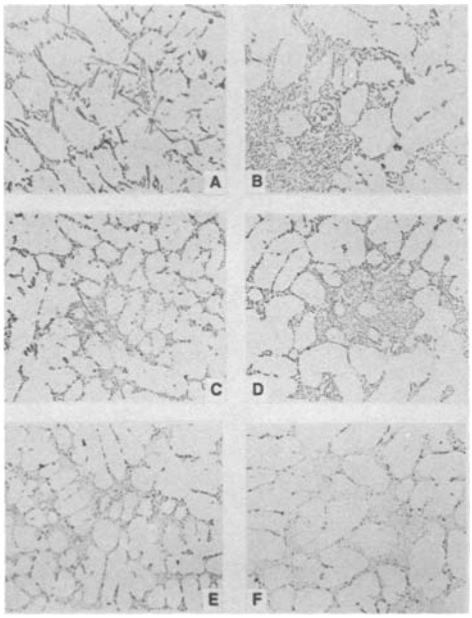
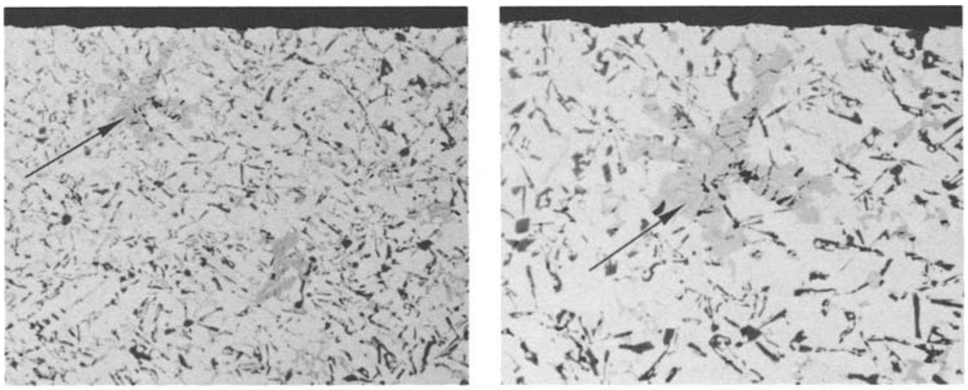


Fig 5 Variation in microstructure as a function of the degree of modification. The modification level increases from A to F; thus microstructure F is highly modified. Source: Ref 2, 12



(a) (b)

Fig 6 Coarse intermetallic $Al_{12}(Fe,Mn,Cr)_3Si_2$ phase constituent generated by entrapped sludge in alloy 339. (a) 130×. (b) 265×

Sarkar attribute the effects of silicon in part to its effect on metal transfer mechanisms between the pin and countersurface (Ref 29). There is also evidence for increased wear resistance with refinement of the silicon particle morphology (Ref 30, 31).

It is clear, therefore, that microstructure-based explanations are needed to account for the variation in wear rates with silicon content. Moreover, there is a need to account for the reduction in strength that occurs with increased silicon content (Ref 32, 33). The complex effects of composition on wear behavior suggest that wear resistance depends on other material properties (for example, fracture toughness) (Ref 34). Thus lower fracture toughness at higher levels of silicon could lead to higher wear rates if larger pieces of debris are created during the wear process. Variations in toughness and strength with composition might also account for the apparent ability of the near-eutectic compositions to have a greater load-bearing capability at a given wear rate than either higher or lower silicon levels.

Matrix Hardness. Increased matrix hardness is typically achieved through the heat treatment response produced by copper and magnesium additions. Most commercial applications of aluminum-silicon alloys, in fact, depend on the increased strength achieved by heat treatment. The improved wear resistance of precipitation-strengthened material compared to solid solution strengthened material under low wear conditions was also noted by Soderberg *et al.* (Ref 35) using aluminum alloy 6061, which is strengthened primarily by Mg_2Si precipitates. This is also the strengthening mechanism in the heat-treatable magnesium-bearing aluminum-silicon alloys. Although heat treatment has a beneficial effect (Ref 26, 27, 32), variations in matrix hardness may be less important than the effects of silicon content (Ref 27).

Intermetallic Constituents. In addition, there are important "other" hard phases present in commercial aluminum-silicon alloys that provide enhanced wear resistance. These constituents (for example, Al-Fe-Si, Al-Fe-Mn, Al-Ni, Al-Ni-Fe, Al-Cu-Mg) have varying degrees of hardness (Ref 36-38). Despite the apparent scatter, these constituents are all much harder than the aluminum matrix. Some examples of the hardness values of these intermetallic compounds are shown in Table 4.

Typical room-temperature hardness values for the aluminum alloy matrices would be <1000 MPa (<100 kgf/mm^2). The hardness values of the intermetallics decrease with increasing temperature (Ref 36), albeit at slower rates than the matrix hardness.

The addition of "hard" phases in the form of particles or fibers to reduce wear is also utilized to create metal-matrix composites (MMC) materials (Ref 39). These materials utilize hard intermetallic, cermet, or ceramic phases to provide the high hardness material for wear resistance. Hornbogen (Ref 40) and Zum Gahr (Ref 41) have described in quantitative terms how the contribution of these hard phases to wear resistance can be modeled in terms of their volume fraction and morphology. This composite approach has been effectively used to develop new piston materials (see the section "Metal-Matrix Composites" in this article).

Table 4 Typical hardness values of selected intermetallic constituents of aluminum-silicon alloys

	Hardness		
Phase	MPa	kgf/mm^2	Ref
$CuAl_2$	3900	400	36, 37
	3800-7600	390-780	36
$FeAl_3$	7200	730	36, 37
	6400-9400	650-960	37
	5160-7110	526-725	36
	3500	360	38
$NiAl_3$	6000-7600	610-770	36
	7100	720	37
	4500	460	38
Ni_2Al_3	9800-11,000	1000-1120	36, 37
Si	7000-14,200	715-1450	36
	11,880	1211	37
Mg_2Si	4480	457	37
Al_2CuMg	3700-3900	380-400	37
Al_9FeNi	8400-9680	860-987	37
$Al_{12}Fe_3Si$	10,760	1097	37

Finally, the use of "softer" constituents (for example, graphite) should also be noted as an active area for development of wear-resistant aluminum-silicon MMC materials (Ref 32, 39, 42). In these materials, ranking may depend on whether volumetric wear rates (in units of m^3/m) or seizure resistance is being considered. The presence of the softer phase may lead to greater volumetric wear in some cases but greater resistance to seizure (higher load at seizure) in other cases.

To summarize, the results of wear studies using aluminum-silicon alloys illustrate a variety of mechanisms. The effect of variations in silicon particle morphology is often not clear cut, although heat treatment is beneficial to the sliding wear resistance. Therefore, selection of an optimum microstructure is often difficult in practical situations where several wear types or mechanisms could occur. In general, either eutectic or hypereutectic alloys offer the greatest wear resistance under a wide range of wear conditions. Selection may then hinge on the dependence of in-service performance on other alloy characteristics or cost. Overall, the aluminum-silicon alloy system provides a good basis for developing lightweight, strong, wear-resistant materials. Examples of these applications will be discussed in the following sections.

Aluminum-Silicon Alloy Applications

Aluminum-silicon alloys are used in a variety of automotive, aerospace, and consumer product applications.

Automotive Components

Table 5 lists typical automotive components made from aluminum-silicon casting alloys (Ref 43). The eutectic or nearly eutectic alloys (for example, 332, 336, and 339) (Ref 44), are perhaps the most widely used. Equivalent versions of these alloys are used for similar applications by European and Japanese automakers (Ref 45-47).

Table 5 Automotive engine applications of aluminum-silicon alloys

SAE alloy	Type of casting(a)	Typical application
319.0	S	General purpose alloy
332.0	PM	Compressor pistons
333.0	PM	General purpose
336.0	PM	Piston alloy (low expansion)
339.0	PM	Piston alloy
355.0	S, PM	Pump bodies, cylinder heads
390.0	D	Cylinder blocks, transmission pump and air compressor housings, small engine crankcase, air conditioner pistons
A390.0	S, PM	Cylinder blocks, transmission pump and air compressor housings, small engine crankcase, air conditioner pistons

(a) S, sand cast; D, die cast; PM, permanent mold. Source: Ref 43

Pistons. Typical applications for aluminum-silicon alloys in the French automotive industry are shown in Table 6 (Ref 45). In addition to being cast, the A-S12UN (eutectic) alloy can also be forged (Ref 48). Similarly, AA 4032, somewhat similar in composition to 336, is also widely used as a piston alloy (for example, for high-performance forged pistons). Hypereutectic alloys are also used for cast pistons, especially in diesel engines (Ref 45, 49). The potential benefit from composites that combine the strength reinforcement of ceramics with an aluminum-silicon alloy matrix has also been evaluated (Ref 45, 47, 48).

Engine Blocks and Cylinder Liners. The evolution of lightweight power plants has depended not only on lightweight pistons but also on the availability of wear-resistant cylinder liners and engine blocks. Hypereutectic liners were described by Mazodier (Ref 50) and El Haik (Ref 51). It was also known that hypereutectic aluminum-silicon alloys had excellent properties for engine blocks (Ref 52-54). This led to the development and application, in both the United States and Europe, of the A390 (A-S17U4) alloys for die cast engines (Ref 55-60). An important aspect of the A390 success is the use of a "system" (Ref 60) that includes the engine alloy, the piston materials (electroplated cast F332[AA 332.0] alloy), and the cylinder bore finishing process. Fine honing to a 0.075 to 0.15 μm (3 to 6 μin.) surface finish, followed by controlled etching/polishing to leave silicon particles standing slightly above the alloy surface, was deemed necessary for optimum wear resistance.

Efforts to simplify the 390-type technology by finding a more wear-resistant alloy for the cylinder or reducing the difficulties of finishing the bore have led to substitute alloys. One approach has been the use of a lower silicon alloy containing more nickel and manganese (for example, the Australian-3HA alloy, with a nominal composition of Al-13.5Si-0.5Fe-0.45Mn-0.5Mg-2Ni) (Ref 61).

Table 6 Selected aluminum-silicon alloy applications in automobiles produced in France according to engine type and specific automobile manufacturer

	Manufacturer			
Engine type	Citroen	Peugot	Renault	Talbot
Gas	A-S12UN	A-S10UN(F)(a)	A-S12UN	A-S10.5UN
	...	A-S12UN(A)(b)	...	A-S11UN
	...	...	...	A-S12UN
Diesel	A-S18UN	A-S12UN	A-S18UN	...
	...	A-S13UN	...	...

(a) F, cast iron liner. (b) A, aluminum block. Source: Ref 45

Continuing interest in the use of more highly wear-resistant materials in other engine-related parts has led to recent applications such as roller-type valve rocker arms (Ref 62) and valve lifters for the Toyota Lexus (Ref 63-64). The rocker arm alloy used in the Mazda 929 is a nominal Al-10Si-2.7Cu-0.8Mg-0.45Mn alloy somewhat similar to the AA 383 alloy. The valve lifter, on the other hand, is a strontium-modified Al-Si-Cu alloy designated 4T12 (composition, Al-10.5Si-4.5Cu-0.6Mg-0.2Mn).

Typical examples from a more detailed compilation of aluminum alloys used in wear-resistant applications in U.S. autos are shown in Table 7.

Bearing Alloy Components. Aluminum alloys have been utilized for bearing applications for many years. The many uses range from diesel and internal combustion engines to a variety of tooling applications (for example, presses, lathes, and milling machines) (Ref 66). Important cast bearing alloys were based on aluminum-silicon or Al-Sn-Cu alloys, whereas wrought bearing alloys have included the 8*xxx* types (for example, AA 8081 and AA 8020) (Ref 66, 67). Compositions of various aluminum bearing alloys are listed in Table 8.

Improved strength and fatigue performance, as well as some increased wear resistance, has been achieved with silicon additions. Thus, alloys SAE 780 and SAE 781 have become widely used for automotive applications such as main and connecting rod bearings (Ref 68, 69). The higher silicon alloy, 781, is also used in bushings and thrust bearings. Its improved wear performance has been attributed to the increased silicon content of the wear surface (Ref 70). These aluminum-silicon alloys are readily used with steel backing in high-load situations.

Advanced Aluminum Bearing Alloys. The nominal compositions of improved bearing alloys with silicon additions are listed in Table 9.

Although a soft phase (for example, tin) is normally considered desirable for avoiding seizure, the compatibility of an Al-11Si-1Cu alloy was better than that of the traditional aluminum-tin alloy (SAE 783) (Ref 71). The silicon-copper alloy also had much better fatigue resistance. The improved properties resulted in applications such as diesel crankshaft and connecting rod bearings. Nevertheless, in line with the concerns expressed by Davies (Ref 72), the harder silicon-containing alloy was more sensitive to misalignment-induced seizure.

The addition of silicon to aluminum-tin alloys containing lower tin levels than that of the 783 alloy provided a compromise between the conformability of the soft-phase material and the benefits of the harder silicon phase for improved wear and fatigue resistance (Ref 73). This alloy could apparently be used without the common lead alloy overlays employed for seizure resistance. The importance of fatigue resistance was also emphasized in the improved Al-Sn-Si alloys reported by Ogita *et al.* (Ref 74). As shown in Table 9, these alloys are somewhat similar to those of Fukuoka *et al.* (Ref 73).

As another alternative to the lead- or tin-containing alloys, a graphite-containing Al-12Si alloy has been successfully evaluated for bearings (Ref 75). The use of a modified lead plus indium addition to an Al-11Si-Pb bearing alloy has also been reported (Ref 76).

Table 7 Wear-resistant aluminum-silicon alloys used in automotive piston components produced for United States automotive manufacturers in 1978 to 1985 model years

Application	Manufacturer	Model/make	Model year(s)
Internal combustion engine components			
Pistons	American Motors	All	1978-85
	Ford	Mercury	1978-81, 83-85
	General Motors	Buick	1978-81, 84-85
		Others	1978-81, 83-85
Brake system components			
Wheel cylinder pistons	American Motors	All	1983-85
	Chrysler	All	1983-85
	Ford	All	1978-85
	General Motors	All (except for Cadillac)	1984-85
		Cadillac	1985
Master cylinder pistons	American Motors	All	1984-85
	Chrysler	All	1984-85
	Ford	All	1983-85
	Ford	Mercury	1978-81, 84-85
	General Motors	All	1984-85
Transmission components			
Intermediate band servo pistons	Ford	Some	1983-85
Rear band servo pistons	Chrysler	Some	1984-85
	Ford	Some	1983-85

Source: Ref 65

Table 8 Nominal compositions of standard aluminum-silicon alloys used in bearing applications

Alloy		Composition, wt%					
Aluminum Association designation	SAE designation	Si	Sn	Cu	Fe	Ni	Cd
850	770	0.7	5.5-7	0.7-1.3	0.7	0.7-1.3	...
8280	780	1-2	5.5-7	0.7-1.3	0.7	0.2-0.7	...
851	...	2-3	5.5-7	0.7-1.3	0.7	0.3-0.7	...
852	...	0.4	5.5-7	1.7-2.3	0.7	0.9-1.5	...
...	781	3.5-4.5	...	0.05-0.15	0.35	...	0.8-1.4
8081	...	0.7	18-22	0.7-1.3	0.7	...	...
...	782	0.3	...	0.7-1.3	0.3	0.7-1.3	2.7-3.5
...	783	0.5	17.5-22.5	0.7-1.3	0.5	0.1	...

Source: Ref 66-68

Table 9 Nominal compositions of advanced aluminum-silicon alloys used in bearing applications

	Composition, wt%						
Alloy(a)	Si	Sn	Cu	Mg	Pb	Other	Ref
A	11	...	1	...	...	...	6
B	3	10	0.4	...	1.8	0.3 Cr	8
C	12	...	1	1.5	...	3 C, 1 Ni	9
D	...	...	4.5	...	...	3 C	...
E	11	...	...	...	20	1.4 In	10
F	2.5	12	1	...	...	0.25 Mn	11
G	6	...	1.2	0.5	1	4 Zn	12
H	4	0.5	0.1	0.1	6	0.3 Mn	13

(a) Arbitrary designations

Japanese concerns with the pollution and toxicity aspects of cadmium-containing alloys have led to improved aluminum-zinc bearing alloys (Ref 77). These have also been improved with silicon additions. The additional matrix wear between the silicon particles is believed to create lubricant reservoirs that enhance seizure resistance. However, overlays (lead-tin alloys) are still required for best conformability.

Finally, the combined effect of silicon and refinement of the silicon- and lead-bearing phases by rapid solidification processing has resulted in an improved Al-6Pb-4Si bearing alloy (Ref 78). This alloy has grown in usage recently and is projected to be used in 78% of the cars built in the United States during 1991.

Because of the increasing understanding of the balance among wear, fatigue, and seizure resistance of bearing materials, silicon alloys have been used to develop new and improved bearing materials. Further improvements will undoubtedly be necessary as engine operating conditions evolve toward higher temperatures and operating speeds.

Consumer Electronics Components

The growth of this market, which encompasses video cassette recorders (VCRs), video tape recorders (VTRs), digital audio tape (DAT) applications, and other devices (for example, personal computers), has created numerous opportunities for the use of lightweight, relatively corrosion-resistant and wear-resistant aluminum-silicon alloys. VTR cylinders are specifically cited by various Japanese authors (Ref 79-81) because the eutectic-type silicon alloys have low coefficients of friction against the tape.

Aerospace Components

A nonautomotive engine application of aluminum-silicon alloys is the use of the 390-type alloys in an aircraft engine (the Thunder engine) (Ref 82).

Breakthroughs in Aluminum-Silicon Wear-Resistant Materials

Metal-Matrix Composites. Composite pistons were recognized early as a potentially viable application of MMC technology. While some composite approaches, especially for the severe operating conditions of diesel pistons, recommended the addition of specific metallic inserts to achieve improved performance (Ref 83), the bulk of development efforts have gone into the incorporation of ceramic fibers.

The use of ceramic fiber aluminum-silicon MMC materials for pistons is described in a variety of publications (Ref 47, 48, 84-88). There are clear benefits to strength at elevated temperatures and reduction of the thermal expansion coefficient. These materials appear to be especially applicable in critical areas such as the top piston rings and top land (a high-temperature area). The castability of the aluminum-silicon alloys is a favorable factor in their use as matrices, particularly because squeeze casting is one of the preferred fabrication routes for composite pistons.

The property improvements at elevated temperatures have encouraged ongoing development of the MMC technology for automotive engine applications, including engine blocks. The ability of the MMC approach to allow selective strengthening of the cylinder region was taken advantage of by Honda engineers (Ref 89), who utilized composite reinforcement of alloy ADC12 (a Japanese alloy similar to 383) in the manufacture of a die cast engine block.

Powder Metallurgy. The combined benefits of high silicon content and refined silicon particle size on wear resistance are strong driving forces behind the use of P/M techniques for making aluminum-silicon alloy parts. The P/M approach has been of special benefit to the hypereutectic silicon alloys. One example of this is the use of P/M A-S17U4 alloy to make cylinder liners (Ref 90, 91). The properties of these alloys exceed those of standard alloys (Ref 92). In addition, high levels of additional elements can be utilized to obtain good strength and wear-resistant properties at elevated temperatures (Ref 93-95).

The refined microstructures available from the P/M fabrication of hypereutectic alloys have a beneficial effect on fatigue characteristics as well. This attribute has been utilized in the production of rotors and vanes for rotary automotive air conditioners (Ref 96). For this application, P/M alloys with high levels of iron or nickel are blended with P/M 2024-type alloys to create alloys containing 17 to 20% Si and 5 to 8% Fe or Ni.

Spray casting, as exemplified by Osprey processing, has been shown to offer benefits similar to powder metallurgy (Ref 97, 98). This has the potential for even greater cost savings, which is an important factor if the aluminum industry is to compete successfully in the automotive market. In a comparison of the structure in an Al-20Si alloy, Kahl and Leupp (Ref 97) showed that there was practically no difference in silicon particle size between the P/M and Osprey processing routes. Furthermore, they claimed that the fine and uniform silicon particle size resulted in improved wear behavior compared with that of conventionally produced material, although details of their test procedure are not known. Earlier work at Delft University (Ref 99) compared the rate of mass loss of an Al-20Si-3Cu-1.3Mg alloy rubbing against cast iron at a pressure level of 5.5 MPa (800 psi). In this test, the Osprey material showed better resistance to wear than either the ingot metallurgy (I/M) or P/M samples. The reason for the better performance of the Osprey product compared with the P/M material was not clear, but it was hypothesized that the slightly larger silicon particles of the Osprey product helped reduce the fretting wear.

Coatings/Surface Treatments. Other approaches to the wear (adhesion) problems of aluminum pistons moving in aluminum cylinders have taken the path of coating or surface treatment of the piston rings and cylinder bore to minimize wear problems (Ref 100). The selective fiber strengthening noted above is related to this problem also. One widely used treatment is the so-called Nikasil treatment (Ref 101), an electrochemical treatment utilizing a dispersion of silicon carbide particles, preferably <4 μm (<160 μin.) in size, in a nickel matrix.

Efforts to take advantage of both the P/M and surface treatment approach are exemplified by the emerging surface treatment technologies of surface alloying via ion implantation (Ref 102-105), thermal spraying (Ref 106-108), and surface treating or alloying using laser treatments (Ref 109-111). Ion implantation is recognized for its ability to impart wear-resistant surfaces, but principal applications have been to protect tool surfaces in critical processing operations. Laser hardening can be achieved through laser cladding to produce a chemically different surface or through the effective heat treatment (or remelting and rapid solidification) brought about by laser heating. The work by Blank *et al.* (Ref 111) using 7 and 12% Si alloys, however, indicated that surface alloying (for example, with iron or iron plus vanadium) was more effective for increased wear than surface heat treatment effects alone. In any case, the ability to tailor surface properties to a technological need will enable engineers to obtain further enhancement of the wear resistance of the aluminum-silicon base alloys without sacrificing their other advantages.

REFERENCES

1. J.P. Lyle and D.A. Granger, *Ullman's Encyclopedia of Industrial Chemistry*, Vol 1A, VCH Publishers, 1985, p 481-528
2. E.L. Rooy, Aluminum and Aluminum Alloys, *Casting*, Vol 15, 9th ed., *Metals Handbook*, ASM International, 1988, p 743-770
3. T.S. Eyre, Wear Resistance of Metals, *Treatise on Materials Science and Technology*, Vol 13, Douglas Scott, Ed., *Wear*, Academic Press, 1979, p 363-442
4. A. Kaye and A. Street, *Die Casting Metallurgy*, Butterworths Scientific, London, 1982, p 32
5. S. Rabinowitz, The Expanding Role of Aluminum in the Automotive Industry, *Die Cast. Eng.*, Sept-Oct 1, 1977
6. J.L. Jorstad, "Aluminum Lightweight Castings—Some Cost Saving Ideas," Paper No. 770322, SAE Automotive Engineering Congress, Society of Automotive Engineers, 1977
7. J.L. Murray and A.J. McAlister, The Aluminum-Silicon System, *Bull. Alloy Phase Diagrams*, Vol 5 (No. 1), 1984, p 74-84, 89-90
8. Registration Record of Aluminum Association, Alloy Designations and Chemical Composition Limits for Aluminum Alloys in the Form of Castings and Ingot, 1987-09-01, Aluminum Association
9. Registration Record of Aluminum Association, Limits for Wrought Aluminum and Wrought Aluminum Alloys, 1987-04-01,

Aluminum Association
10. L.F. Mondolfo, *Aluminum Alloys: Structure and Properties*, Butterworths, 1976
11. D.A. Granger, R.R. Sawtell, and M.M. Kersker, Effect of Beryllium on the Properties of A357.0 Castings, *Trans. AFS*, 1984, p 579-586
12. D.A. Granger and R. Elliott, Aluminum-Silicon Alloys, *Casting*, Vol 15, 9th ed., *Metals Handbook*, ASM International, 1988, p 159-168
13. J.E. Hatch, *Aluminum: Properties and Physical Metallurgy*, American Society for Metals, 1984, p 344-345
14. *Source Book on Selection and Fabrication of Aluminum Alloys*, American Society for Metals, 1978
15. A.L. Kearney and E.L. Rooy, Aluminum Foundry Products, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, Vol 2, *ASM Handbook*, ASM International, 1990, p 123-151
16. A.L. Kearney, Properties of Cast Aluminum Alloys, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, Vol 2, *ASM Handbook*, ASM International, 1990, p 152-177
17. J.E. Hatch, Chapters 8 and 9, *Aluminum: Properties and Physical Metallurgy*, American Society for Metals, 1984, p 152-177
18. General Information—Chemical Compositions, Mechanical and Physical Properties of SAE Aluminum Casting Alloys—SAE J452, June 1983, *SAE Handbook*, Society of Automotive Engineers, 1989, p 10.5-10.13
19. R.E. Spear and G.R. Gardner, Dendrite Cell Size, *Trans. AFS*, Vol 71, 1963, p 209-215
20. D.V. Neff, Non-Ferrous Molten Metal Processes, *Casting*, Vol 15, 9th ed., *Metals Handbook*, ASM International, 1988
21. J. Gobrecht, Gravity-Segregation of Iron, Manganese and Chromium in an Aluminum-Silicon Casting Alloy, Part I, *Giesserei*, Vol 62 (No. 10), 1975, p 263-266; and D.A. Granger, Investigation of a Star-Like Intermetallic Phase Occurring in Alloy 339, *Trans. AFS*, Vol 91, 1991, p 379-383
22. K. Mohammed Jasim and E.S. Dwarakadasa, Wear in Al-Si Alloys under Dry Sliding Conditions, *Wear*, Vol 119, 1987, p 119-130
23. B.N. Pramila Bai and S.K. Biswas, Effect of Load on Dry Sliding Wear of Aluminum-Silicon Alloys, *ASLE Trans.*, Vol 29 (No. 1), 1986, p 116-120
24. R. Shivanath, P.K. Sengupta, and T.S. Eyre, Wear of Aluminum-Silicon Alloys, *Wear of Materials—1977*, International Conference on Wear of Materials, W. Glaeser, K. Ludema, and S. Rhee, Ed., American Society of Mechanical Engineers, p 120-126
25. R. Antoniou and D.W. Borland, Mild Wear of Al-Si Binary Alloys during Unlubricated Sliding, *Mater. Sci. Eng.*, Vol 93, 1987, p 57-72
26. J.B. Andrews, M.V. Seneviratne, K.P. Zier, and T.R. Jett, The Influence of Silicon Content on the Wear Characteristics of Hypereutectic Al-Si Alloys, *Wear of Metals—1985*, K. Ludema, Ed., American Society of Mechanical Engineers, p 180-184
27. J.B. Andrews, M.V. Seneviratne, and T.R. Jett, The Influence of Si and Other Alloying Additions on the Wear Characteristics of Hypereutectic Al-Si Alloys, *4th European Tribology Congress (EUROTRIB 85)*, Vol III, 1985
28. J. Clarke and A.D. Sarkar, Wear Characterization of As-Cast Binary Aluminum-Silicon Alloys, *Wear*, Vol 54, 1979, p 7-16
29. J. Clarke and A.D. Sarkar, The Role of Transfer and Back Transfer of Metals in the Wear of Binary Al-Si Alloys, *Wear*, Vol 82, 1982, p 179-185
30. T.K.A. Jaleel, N. Raman, S.K. Biswas, and K.K. Murthy, Effect of Structural Modification and Load on the Wear of a Hypereutectic Aluminum-Silicon Alloy, *Aluminium*, Vol 60 (No. 12), 1984, p 932-933
31. Y. Odani, K. Akechi, and N. Kuroishi, High Strength and High Wear Resistance Al-Si P/M Alloys, *Modern Developments in Powder Metallurgy*, Vol 16, 1984, p 493-505
32. S. Das, S.V. Prasad, and T.R. Ramachandran, Microstructure and Wear of Cast (Al-Si Alloy) Graphite Composites, *Wear*, Vol 133, 1989, p 173-187
33. B.N. Pramila Bai, S.K. Biswas, and N.N. Kumtekar, Scanning Electron Microscopy Study of Worn Al-Si Alloy Surfaces, *Wear*, Vol 87, 1983, p 237-249
34. K.-H. Zum Gahr, Microstructure and Wear of Materials, *Tribology Series*, Vol 10, Elsevier, 1987
35. S. Soderberg, U. Bryggman, and A. Canales, Influence of Precipitation and Solution Strengthening on Abrasive Wear Resistance, *Wear of Metals—1985*, K. Ludema, Ed., American Society of Mechanical Engineers, p 645-653
36. E.R. Petty, Hot Hardness and Other Properties of Some Binary Intermetallic Compounds of Al, *J. Inst. Met.*, Vol 89, 1960-1961, p 343-349
37. A.A. Ivanko and G.V. Samsonov, *Handbook of Hardness Data*, Translation from Russian, National Bureau of Standards-National Science Foundation, 1968
38. H.E.N. Stone, The Oxidation Resistance, Hardness and Constitution of Metallic Aluminides, *J. Mater. Sci.*, Vol 10, 1975, p 923-934
39. S.V. Prasad and P.K. Rohatgi, Tribological Properties of Al Alloy Particle Composites, *J. Met.*, Nov 1987, p 22-26
40. E. Hornbogen, Description of Wear of Materials with Isotropic and Anisotropic Microstructure, *Wear of Metals—1985*, K. Ludema, Ed., American Society of Mechanical Engineers, p 477-484
41. K.-H. Zum Gahr, Abrasive Wear of Two Phase Metallic Material with a Coarse Microstructure, *Wear of Metal—1985*, K. Ludema, Ed., American Society of Mechanical Engineers, p 45-57
42. B.N. Pramila Bai, E.S. Dwarakadasa, and S.K. Biswas, Scanning Electron Microscopy Studies of Wear in LM13 and LM13-Graphite Particulate Composite, *Wear*, Vol 76, 1982, p 211-220
43. General Information—Chemical Compositions, Mechanical and Physical Properties of SAE Aluminum Casting Alloys, *SAE Handbook*, J452, June 1983, Society of Automotive Engineers
44. R. Wilson, Piston Improvement Relies on Material Science, *Diesel Prog. North Am.*, Vol 52 (No. 2), Feb 1986, p 18-20
45. J. Ayel, The Influence of Metallurgical and Geometric Parameters on the Wear of Recent Engines, *Ing. Automob.*, Sept-Oct 1980, p 82-98
46. M. Coulondre and J. Travaille, New Trends in the Design and Manufacture of Pistons and Cylinders for Automobile Engines, *Ing. Automob.*, Sept-Oct 1980, p 68-72
47. A.R. Baker and S. Gazzard, Developments in Materials for Pistons, *Mater. Des.*, Vol 9 (No. 1), Jan-Feb 1988, p 28-33
48. J.C. Avezou and A. Parker, Evolution of Materials for Pistons, Segments and Valve Seatings for Petrol and Diesel Engines of Automobiles, *Ing. Automob.*, Oct 1983, p 73-80
49. J.P. Whitacre, "Hypereutectic Aluminum—A Piston Material for Modern High Specific Output Gasoline Engines," TP 871944, Society of Automotive Engineers, 1987
50. M. Mazodier, Aluminum Engine Blocks with Thin Hypersilicon Alloy Liners, *Ing. Automob.*, No. 10, Oct 1977, p 586-590
51. R. El Haik, The Possibilities of Using Al Cylinder Blocks—Hypersiliconized Cylinder Liner Tests, *Ing. Automob.*, No. 10, Oct 1977, p 569-577
52. J.L. Jorstad, "Development of the Hypereutectic Al-Si Die Casting Alloy Used in the Vega Engine Block," TP No. 105, 6th International Society of Die Casting Engineers Congress (Cleveland, OH), Nov 1970
53. J.L. Jorstad, The Hypereutectic Aluminum-Silicon Alloy Used to Cast the Vega Engine Block, *Mod. Cast.*, Vol 60 (No. 4), Oct 1971, p 59-64
54. J. Ayel, Frictional Behavior of the Aluminum Hypersilicon Alloys Used as Engine Liners, *Rev. Alum.*, Apr 1978, p 186-191
55. H.H. Hofmann and K. Schellmann, "Aluminum 390 Alloy Engine Blocks: Design and Manufacturing," TP 830007, Society of Automotive Engineers, 1983

56. W. Dahm and R.G. Putter, "Light Alloy Engines—Experience Gained from Research and Development," TP 830005, Society of Automotive Engineers, 1983
57. G. Renninger, D. Abendroth, and M. Bolien, "Casting Engine Blocks in GK Al Si 17 Cu 4 Mg," TP 830003, Society of Automotive Engineers, 1983
58. E.G. Jacobsen, "General Motors 390 Aluminum Alloy 60 degree V6 Engine," TP 830006, Society of Automotive Engineers, 1983
59. H.M. Ward, III, "Engineering Control for High Volume 390 Die Casting," TP 830009, Society of Automotive Engineers, 1983
60. J.L. Jorstad, "Reynolds 390 Engine Technology," TP 830010, Society of Automotive Engineers, 1983
61. J. Barresi, R. Giannini, and B.J. Clarsen, "Cold Scuff Evaluation of 3HA—The Engine Alloy Developed in Australia," TP 871203, Society of Automotive Engineers, 1987
62. S. Komatsu, S. Yahata, K. Fukui, and T. Tokoshima, "Development of Aluminum Alloy Roller Type Valve Rocker Arm by Casting and Forging Technique," TP 890554, Society of Automotive Engineers, 1989
63. S. Ezaki, M. Masuda, H. Fujita, S. Hayashi, Y. Terashima, and K. Motosugi, "Aluminum Valve Lifter for Toyota New V-8 Engine," TP 900450, Society of Automotive Engineers, 1990
64. H. Baker, The Road Ahead for Metals in Autos, *Adv. Mater. Proc.*, May 1990, p 27-34
65. Aluminum Association Guide to Aluminum Parts 1978-1984, Reynolds Aluminum 1985 Aluminum Automotive Applications
66. Chapter 20, *Aluminum—Vol II: Design and Application*, K.R. Van Horn, Ed., American Society for Metals, 1967
67. Chapters 8 and 9, *Aluminum—Vol I: Properties, Physical Metallurgy and Phase Diagrams*, K.R. Van Horn, Ed., American Society for Metals, 1967
68. "Bearing and Bushing Alloys," J460e, *SAE Handbook*, Society of Automotive Engineers
69. "Bearing and Bushing Alloys," J459c (Information Report), *SAE Handbook*, Society of Automotive Engineers
70. M. Gallerneaut and C. Fulton, "Score Resistance of SAE 781 Automotive Journal Bearing Alloy-A Metallographic Analysis," TP 860062, Society of Automotive Engineers, 1986
71. G.C. Pratt, "Aluminum Based Crankshaft Bearings for the High Speed Diesel Engine," TP810199, Society of Automotive Engineers, 1981
72. F.A. Davis, Plain Bearing Wear in Internal Combustion Engines, *Automot. Eng. (UK)*, Vol 6 (No. 4), 1981, p 31-33, 37-38
73. T. Fukuoka, H. Kato, and S. Kamiya, Aluminum Alloy Bearings Containing Hard Particles Fitted for Use with Nodular Iron Shaft, *Studies of Engine Bearings and Lubrication*, SP-539, Society of Automotive Engineers, 1983, p 33-44 (TP 830308)
74. Y. Ogita, K. Niwa, and Y. Kondo, "New Engine Type Fatigue Phenomenon of Al-Based Engine Bearings," TP 890556, Society of Automotive Engineers, 1989
75. B.P. Krishnan, N. Raman, K. Narayanaswamy, and P.K. Rohatgi, Performance of Aluminum Alloy Graphite Bearings in a Diesel Engine, *Tribol. Int.*, Vol 16 (No. 5), 1983, p 239-244
76. D.P. Howe and J.D. Williams, An Al-Si-Pb-In Plain Bearing Material, *Proceedings Fourth Conference of Irish Durability and Fracture Committee* (IDFC4), 1986, p 183-191
77. M. Sakamoto, Y. Ogita, Y. Sato, and T. Tanaka, "Development of New Al-Zn-Si Bearings for Heavy Load Applications in Uprated Engines," TP 900124, Society of Automotive Engineers, 1990
78. *Automot. Eng.*, Vol 97 (No. 12), 1989, p 21-25
79. S. Kitaoka, H. Kamio, and S. Kobayashi, Material Properties of Al-Si Alloys for Forging and Their Application, translation from *Alutopia (Jpn.)*, Vol 17 (No. 10), 1987, p 9-18
80. S. Kitaoka, C. Fujikura, and A. Kamio, Aluminium-Silicon Alloys, translation of *J. Jpn. Inst. Light Metals*, Vol 38 (No. 7), 1988, p 426-446
81. O. Takezoe and Y. Yasuda, Technical Trends of Highly Wear Resistant Aluminum Alloy, *Kobe Res. Dev.*, Vol 38 (No. 4), Oct 1988, p 23-26
82. R.P. MacCoon and R.P. Ernst, "The Thunder Aluminum 390 Alloy Aircraft Engine," TP 830008, Society of Automotive Engineers, 1983
83. *Automot. Eng. (London)*, Vol 7 (No. 3), June-July 1982, p 25-27
84. M.W. Toaz and M.D. Smalc, Clevite's Advanced Technology for the Diesel Piston, *Diesel Prog. North Am.*, Vol 51 (No. 6), June 1985, p 56
85. R.R. Bowles, D.L. Mancini, and M.W. Toaz, Design of Advanced Diesel Engine Pistons Employing Ceramic Fiber Reinforcement, *Seminar—Advanced Composites: The Latest Developments*, Nov 1986, American Society for Metals, p 21-27
86. T. Donomoto, K. Funatani, N. Miura, and N. Miyake, "Ceramic Fiber Reinforced Piston for High Performance Diesel Engines," TP 830252, Society of Automotive Engineers, 1983
87. T. Suganuma and A. Tanaka, Applications of Metal Matrix Composites to Diesel Engine Pistons, *J. Iron Steel Inst. Jpn.*, Vol 75 (No. 9), Sept 1989, p 1790-1797
88. R. Keribar, T. Morel, and M.W. Toaz, "An Investigation of Structural Effects of Fiber Matrix Reinforcement in Aluminum Diesel Pistons," TP 900536, Society of Automotive Engineers, 1990
89. T. Hayashi, H. Ushio, and M. Ebisawa, "The Properties of Hybrid Fiber Reinforced Metal and Its Application for Engine Block," TP 890557, Society of Automotive Engineers, 1989
90. R. Perrot, Engine Sleeves Made in a Hypereutectic Aluminium-Silicon Alloy by Powder Metallurgy, *European Symposium on Powder Metallurgy* (Stockholm), Vol 2, 1978, p 212-217
91. R. Perrot, Engine Cylinder Liners in High Silicon Aluminum Alloy Produced by Powder Metallurgy, *Rev. Alum.*, Mar 1979, p 129-135
92. N. Kuroishi, Y. Odani, and Y. Takeda, High Strength High Wear Resistance Aluminum-Silicon P/M Alloys, *Met. Powder Rep.*, Vol 40 (No. 11), Nov 1985, p 642-645
93. J.L. Estrada and J. Duszczyk, Characteristics of Rapidly Solidified Al-Si-X Powders for High Performance Applications, *J. Mater. Sci.*, Vol 25 (No. 2A), Feb 1990, p 886-904
94. K. Hummert and V. Arnhold, Possibilities of Powder Metallurgy Aluminum Materials in Motor Construction, *3rd International Symposium on Aluminium + Automobile*, 1988, p 171-175
95. "High Strength Aluminium Alloy Powder Having Heat and Wear Resistance: Contains Silicon, Nickel, Iron and Manganese, and is Used for Cylinder Liners," U.S. patent 4,938,810
96. T. Hayashi, Y. Takeda, K. Akechi, and T. Fujiwara, "Rotary Car Air Conditioner Made with P/M Al-Si Wrought Alloys," TP900407, Society of Automotive Engineers, 1990
97. W. Kahl and J. Leupp, "High Performance Aluminum Produced by Spray Deposition," BNF 7th International Conference Material Revolution through the 90s
98. F. Hehemann *et al.*, "Comparison of Processing Atomized and Spray-Deposited Al-20 Si-5 Fe-2 Ni (wt.%) Aimed at Automotive Applications," PM90, Institute of Metals, London
99. J. Duszczyk *et al.*, The Osprey Preform Process and the Application to Aluminum Alloys Including Wear and High Temperature Resistance Al-20 Si-Cu Alloys, *Modern Developments in Powder Metallurgy*, Vol 18-21, Metal Powder Industries Federation, 1988, p 441-453
100. D.A. Parker, Material Innovation and Its Impact on the Development of Components for Reciprocating Engines, *Int. J. Veh. Des.*, IAVD Congress on Vehicle Design and Components, 1985, Interscience Enterprises, Ltd., United Kingdom, p B35.1-30
101. A.E. Ostermann, "Experiences with Nickel-Silicon Carbide Coatings in Cylin-

der Bores of Small Aluminum Engines," TP 790843, Society of Automotive Engineers, 1979

102. J.D. Destefani, Ion Implantation Update, *Adv. Mater. Proc.*, Oct 1988, p 39-43
103. C.M. Preece and J.K. Hirvonen, *Ion Implantation Metallurgy*, TMS-AIME, 1980
104. I.L. Singer, Tribomechanical Properties of Ion Implanted Metals, *Ion Implantation and Ion Beam Processing of Materials*, MRS Symposia Proceedings, Materials Research Society, Vol 27, 1983, p 585-595
105. J.H. Hirvonen, Industrial Applications of Ion Implantation, *Ion Implantation and Ion Beam Processing of Materials*, MRS Symposia Proceedings, Materials Research Society, Vol 27, 1983, p 621-629
106. G.L. Kutner, Thermal Spray by Design, *Adv. Mater. Proc.*, Oct 1988, p 63
107. M.L. Thorpe, Thermal Spray Applications Grow, *Adv. Mater. Proc.*, Oct 1988, p 69
108. E.J. Kubel, Jr., Thermal Spraying Technology: From Art to Science, *Adv. Mater. Proc.*, Dec 1987, p 69
109. C.W. Draper, Laser Surface Alloying: The State of the Art, *J. Met.*, June 1982, p 24
110. J.M. Rigsbee, Surface Engineering by Laser and Physical Vapor Deposition Techniques, *J. Met.*, Aug 1984, p 31
111. E. Blank, M. Pierantoni, and M. Carrard, Laser Surface Modification of Al-Si Cast Alloys for Wear Resistance and Surface Toughness, *Surface Modification Technologies III*, 1990, T.S. Sudarshan and D.G. Bhat, Ed., TMS-AIME, 1990, p 493-510