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An Overview of the Development of Al-Si-Alloy Based Material for Engine Applications

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The development of Al-Si alloy and its based material for engine application is reported in this paper, focusing on improving the material's fatigue limit and wear resistance, which are two important properties for engine block materials. The paper begins with a description of the microstructure (primary and eutectic phases, intermetallics, and casting defects) of Al-Si alloy and its effects on this material's fatigue and wear behaviors. Then, some recent techniques to enhance these two properties are discussed such as alloying, composite production, and casting.

Keywords Al-Si alloy, materials fatigue, wear behavior

1. Introduction

Due to economic and environmental requirements, it is becoming increasingly important to reduce vehicle weight. For such an objective, Al-Si alloys such as Al 356.0 (Al-7Si-0.3Mg) and Al 390.0 (Al-17.0Si-4.5Cu-0.6Mg)[1] have been commercially used to produce an engine block due to their high strength over weight ratio.

The engine block works under mechanical and thermal cyclic stresses in relative motion with other engine parts. High fatigue strength and good wear resistance are critical properties to engine block life. Under cyclic stresses, microcracks can initiate at some stress concentration sites and then propagate until the final failure of a material. The whole fatigue process largely depends on the microcrack initiation and propagation as the final failure of the material happens quite quickly. In high cycle fatigue, as the cyclic stress is comparatively low, a large fraction of the fatigue life is used in microcrack initiation. Wear is another major failure of engine block material. This process is attributed to a couple of factors. First, the presence of hard particles and chemicals in cooling and lubrication fluid results in abrasive and corrosive wear. Second, erosive wear is also significant from the impact of hot air and gases. Third, friction between the block wall and piston ring can produce adhesion even in oil lubrication. Finally, fatigue also contributes to the wear of engine block.

In addition to high fatigue strength and wear resistance, engine block material is also supposed to possess good castability and machinability. This is because engine block has a very complex structure. It is initially cast and thereafter subject to mechanical machining.

2. The Microstructure and Casting Defects in Al-Si Alloy

2.1 Primary and Eutectic Phases

Al-Si binary alloy is a eutectic system with the eutectic composition at 12.6 wt.% Si (Fig. 1).[2] Silicon reduces the thermal expansion coefficient, increases corrosion and wear resistance, and improves casting and machining characteristics of the alloy. When the Al-Si alloy solidifies, the primary aluminum forms and grows in dendrites or silicon phase forms and grows in angular primary particles. When the eutectic point is reached, the eutectic Al-Si phases nucleate and grow until the end of solidification. At room temperature, hypoeutectic alloys consist of a soft and ductile primary aluminum phase and a hard and brittle eutectic silicon phase. Hypereutectic alloys usually contain coarse, angular primary silicon particles as well as a eutectic silicon phase.

2.2 Intermetallic Precipitates

The Al-Si alloy usually has some other coexisting elements such as copper, magnesium, manganese, zinc, and iron. The solubility of these elements in aluminum usually increases with increasing temperature. This decrease from high concentrations at elevated temperatures to relatively low concentrations during solidification and heat treatment results in the formation of secondary intermetallic phases. For instance, the precipitation of Si, Mn, and Fe forms an $Al_{12}(Fe,Mn)_3Si$ phase. The wide variety of intermetallic phases in aluminum alloys occur because aluminum is highly electronegative and trivalent, which has been the subject of considerable study.[3-5]

2.3 Casting Defects

Cast Al-Si alloys usually have casting defects such as porosity and inclusion, which can greatly degrade the mechanical properties of the materials. Porosity is the most common defect in Al-Si castings. In addition to the fact that a pore cannot sustain external load, more seriously, it is a kind of stress concentrator, and thus can lead to microcrack initiation and propagation.

Microporosity usually results from exsolution of dissolved gas from the melt and/or failure of interdendritic feeding. The

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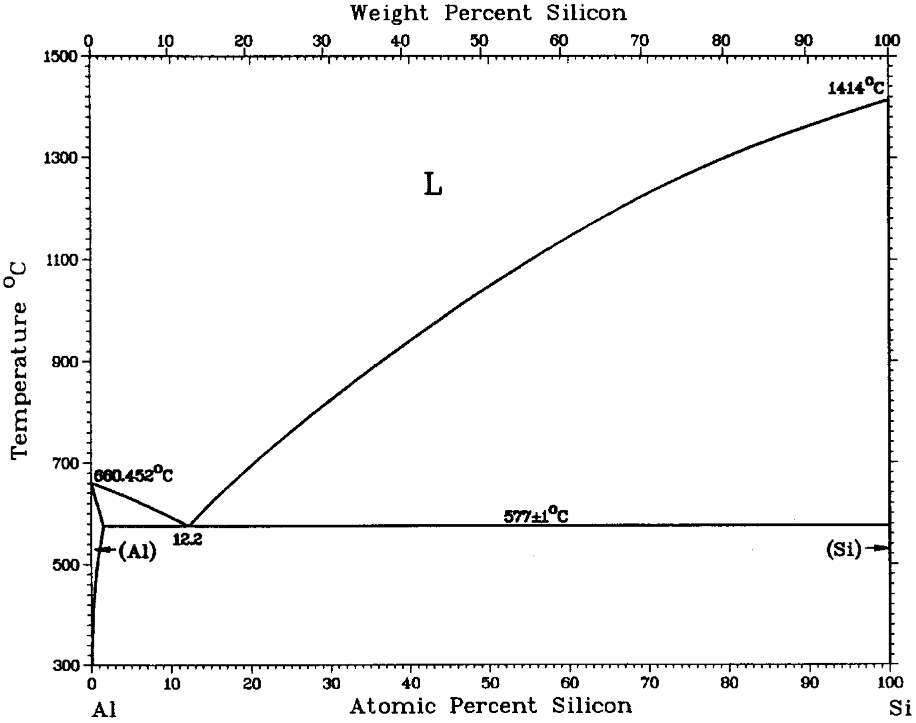

Fig. 1 The Al-Si binary phase diagram

solubility of hydrogen in Al-Si melt increases as temperature increases. When molten Al-Si alloy solidifies, the hydrogen atoms precipitate from the melt and form molecular hydrogen. If alloy solidifies faster than the molecular hydrogen escapes from the melt, gas porosity will be generated in the solid alloy. On the other hand, a lot of dendritic structures form in Al-Si alloy during its solidification. These dendrites take space in the melt, and reduce the fluidity of melt. Thus the shrinkage in the melt between the dendrites cannot be fully filled, and microporosity is formed along these dendrites after the melt solidification.

Alloying elements greatly influence porosity formation via a few mechanisms. First, an alloying element can change the freezing range of Al-Si alloy so that the porosity can be changed. When the freezing range is decreased, the "mushy zone" in the solidifying material is reduced and thus the porosity is reduced. Second, alloying element can form dendritic intermetallics during solidification. Porosity can form along these intermetallic dendrites. A study of the microstructure of an Al-9 wt.% Si-3 wt.% Cu alloy reveals that pores can nucleate along the long sides of the β-Al_5FeSi needles.[6] Third, alloying elements can form a low melting point phase and cannot be filled when solidifying between dendrites. A study of an Al-Si-Mg alloy modified with Sr found that a Cu content over 0.2% resulted in a 7-fold increase of the dispersed microporosity.[7] The mechanism is that Cu forms some interdendritic Cu-rich phases, which solidify at a lower temperature and thus cannot be fully filled. The relationship between the porosity fraction and Cu content is shown in Fig. 2. Fourth, alloying elements can form high melting point phases in the melt, reducing the fluidity of the melt and thus helping to produce porosity. Finally, the alloying elements such as sodium, phosphorus, titanium, and boron in modifying silicon phase morphology or refining grains also have effects on porosity formation. In general, the addition of grain refiners increases the number of grain nucleation sites and reduces grain size. Accompanying this grain refinement is a decrease in volume fraction and size of pores and increase in the homogeneity of the pore distribution. Silicon refining also has an influence on the formation of the porosity. In hypereutectic alloys, phosphorus is added to form AlP particles as the nucleation site for primary silicon. It was found that the addition of 19 ppm phosphorus noticeably reduces the percentage porosity in the Al-9 wt.% Si-3 wt.% Cu alloy.[6] Modification in the Al-Si alloy refines the eutectic phase particles shape and improves the casting's mechanical property, but it usually increases the porosity.

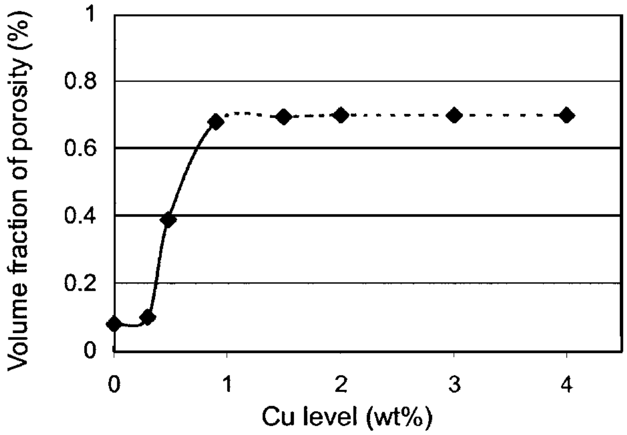

Fig. 2 The effects of Cu content on porosity fraction in Al-Si alloy

These changes may be due to various possible mechanisms: the modifier increases inclusion content in the melt, decreases hydrogen solubility in solid metal, and/or increases the volumetric shrinkage. However, compared with the influence from hydrogen concentration in the melt, modification usually has a smaller effect on the formation of the porosity.

Nonmetallic inclusion is another common defect in cast Al-Si alloys. Oxide and silicate are the most ordinary representatives and are usually produced during the melting and feeding processes. Inclusions usually have a weak interface with the matrix and form a cluster or network. They are usually not bonded at their interface with each other. Therefore, cracks can be easily produced at the interface between themselves or the interface between matrix and inclusion when the material is subject to an external load. Once the microcracks are produced, the fatigue and wear resistance are both reduced.

3. The Effects of Microstructure and Casting Defects on Mechanical Properties of Al-Si Alloy

3.1 The Effects of Primary and Eutectic Microstructures

Fatigue occurs in Al-Si alloy mainly by nucleation and propagation of microcracks around silicon phase or in aluminum matrix. Silicon is brittle and can easily crack. Decohesion of silicon from the aluminum matrix also takes place. Microcracks usually initiate from these sites and then propagate. The following microstructure features can significantly affect the fatigue crack initiation and growth behavior: dendrite arm spacing (DAS), size and distribution of silicon particles, fracture resistance of silicon, and strength of interface between silicon and aluminum matrix. The effect of dendrite cell size and DAS on the fracture path has been studied in tensile tests of a cast A356/357 Al alloy.[8] In large cell and DAS samples, the cell boundaries are well defined by a high density of silicon particles. In small cell and DAS samples, the silicon particles in the cell boundaries are further apart but more of them are on grain boundaries. The fracture path in the samples of large DAS is mainly along cell boundaries where there is high density of cracked silicon particles, while in the small DAS samples, the fracture path is along grain boundaries and the cracked silicon particles are also evident.

The effects of eutectic silicon particle size and morphology on fatigue crack growth behavior were studied with an Al-Si-Mg cast alloy under the constant load amplitude condition. It reveals that refining of eutectic silicon particles improves fatigue crack growth resistance (Fig. 3).[9]

Crack initiation and propagation also occur in the reinforcement free area of matrix. The dislocation slip band in the matrix is a kind of microcrack initiator. The matrix has areas where there is no reinforcement such as silicon particles or intermetallic precipitates. These local non-reinforced areas are relatively soft and dislocation slip can be easily produced under external stress. When the slips accumulate at part surface or grain boundaries, a localized strain is produced and an even microcrack is initiated. Accordingly, fatigue behavior of the Al-Si alloy is expected to improve if the fatigue deformation is dispersed more uniformly so that the large localized strain can be avoided. Hence, when some finely dispersed particles are introduced into the alloy so that the slip is dispersed and fatigue crack initiation is delayed, the fatigue strength of the material improves. For instance, when the fatigue behaviors of a commercial purity (7075) and high purity (X-7075) Al-Zn-Mg-Cu alloys are compared, the commercial purity alloy has a higher fatigue life (Fig. 4).[10] This is because a commercial purity alloy has some magnesium and chromium that produce some fine $Al_{12}Mg_2Cr$ precipitates in the alloy, which strengthen the matrix. However, the second phase precipitates may also speed up the fatigue process if some cracks preexisted. In this case, debonding of matrix and particle or breaking of the second phase itself will accelerate the propagation of the fatigue cracks. Additionally, surface roughness also influences fatigue behavior. A rough surface usually offsets fatigue limit enhancement resulting from the internal microstructure improvement.

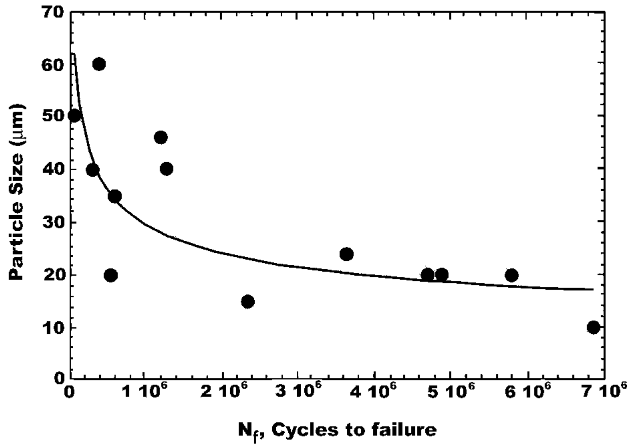

Fig. 3 The effect of silicon particle size on fatigue life of Al-Si alloy

The major mechanism responsible for the wear of aluminum silicon alloy is the delamination of surface material. The breaking of silicon particles or silicon and matrix interfaces can initiate microcracks. These microcracks propagate along the subsurface until they reach the surface, where the whole piece of material is removed. Simultaneously, external abrasives can cut off the soft aluminum matrix by local plastic deformations, if there is no protection from the secondary hard phase.

Silicon particles have been found to be important to the wear resistance of Al-Si alloy. At a relatively low load, wear resistance is not strongly affected by the silicon content. However, as the load increases, addition of silicon into Al-Si alloy increases the wear resistance (Fig. 5).[11] Both the transition loads from mild wear to intermediate wear and from intermediate wear to severe wear of the Al-Si alloy increase with the increase in silicon content. The hypoeutectic and hypereutectic Al-Si alloys have both been used as tribological material in engine applications. However, hypereutectic Al-Si alloy can be used to produce engine block without cylinder liner as it has a higher wear resistance resulting from a larger fraction of silicon phase. Usually, the hypereutectic Al-Si alloy engine block surface is electrochemically treated to etch away some of the matrix aluminum alloy so that the eutectic and primary silicon particle can protrude to sustain wear.

The general mechanism responsible for such an increase in the wear resistance of Al-Si alloy is that silicon increases the overall hardness of the alloy and thus makes it more resistant

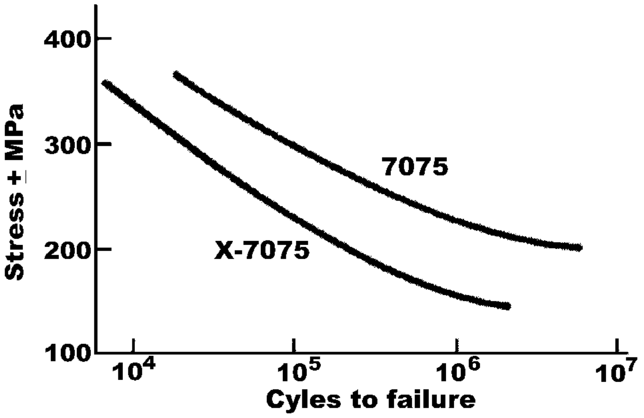

Fig. 4 The fatigue behavior of Al-Zn-Mg-Cu alloys with different purities

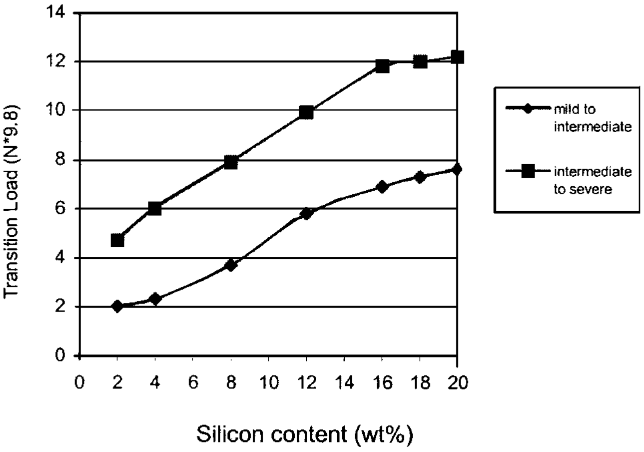

Fig. 5 Influence of silicon content on wear resistance of Al-Si alloy

to wear. However, this does not always mean that the higher the fraction of silicon in the alloy, the greater the wear resistance in the alloy. Due to its high brittleness, impact load can break silicon and thus may increase the overall wear of the alloy. This is especially true when the silicon phase has a coarse morphology. So the optimal fraction of silicon in Al-Si alloy relies on the material's service condition and silicon morphology.

3.2 The Effects of Intermetallics and Casting Defects

The intermetallic phase has a large effect on both fatigue and wear performance of Al-Si alloy. These second phases are usually hard compared with the matrix. If the second phases are finely dispersed, they can block dislocation slip or microcrack growth and also sustain the external load and thus improve the fatigue limit and wear resistance. But if they are coarse, they can easily break and produce microcracks and then reduce the fatigue and wear resistance. The shape of the second phase is also an influence on the matrix property. Usually, a sharp second phase raises a higher stress concentration and more easily initiates microcrack. For instance, iron aluminum intermetallics appear in Al-Si alloy with different types and configurations.

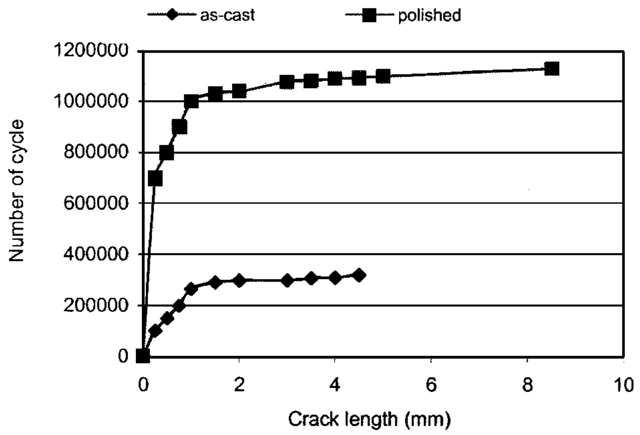

Fig. 6 The fatigue strength of polished and as-cast Al-7Si-Mg samples

The most detrimental one is the needle-like β-Al_5FeSi intermetallics. This brittle phase cuts the matrix and produces stress concentration and thus greatly degrades the mechanical properties of Al-Si alloy.[6]

Size and morphology of casting defects are important factors that determine their effects on a material's properties. In general, big and sharp defects produce larger deterioration of the material's properties. Distribution of the defects is another important factor that determines the effects of the defects. Fatigue resistance is a function of the local microstructure in the casting. For example, the microstructural heterogeneity of aluminum A356 permanent mold castings impacts fatigue performance differently, depending on the location in the casting.[12] Local fatigue resistance decreases greatly in specimens taken from the outside of the overflow end to the center of the gate end of the bar. The former includes the first metal to freeze, while the latter the last metal to freeze. The amount of Al-Si eutectic and the density of micro-porosity increase along the solidification path. Therefore, microcracks can take place and propagate easier in the area of high volume fraction of defects and Al-Si eutectic. Studies have shown that surface or subsurface defects have the largest reduction on alloy's fatigue resistance as the crack initiator. The fatigue behaviors of a polished and an as-cast Al-7Si-Mg alloy have been studied. The fatigue strength from a polished sample, which has many fewer casting defects, is much higher than that of as-cast sample (Fig. 6).[13] The defect distribution varies with casting solidification so that the casting can be designed to locate the defects at the area where the material's fatigue resistance is less reduced by the defects.

Wear is a surface process. It is evident that surface defects are more detrimental to the wear resistance of a material than the defects in the center of the material.

4. Techniques for Property Improvement of Al-Si Alloy

4.1 Alloying

Apart from the small amount of coexisting elements in Al-Si alloy, some elements are intentionally added into the Al-Si melt to a significant quantity so that the alloy's sensitivity to heat treatment and microstructure is changed. Thus alloying has become an effective method to improve the mechanical properties of Al-Si alloy.

The alloying elements often used in the Al-Si alloy include iron, magnesium, copper, manganese, nickel, zinc, lead, and phosphorus. Iron can be tolerated up to a level of 1.5-2.0%. Iron can modify the silicon phase by inducing several Al-Fe-Si phases and it is often used to prevent die sticking in die-casting. Magnesium can strengthen the material through precipitation of fine Mg_2Si in matrix. Copper can additionally strengthen the alloy by precipitation of $AlCu_2$ or modification of the brittle Al-Fe-Si phases. Copper also improves the corrosion resistance of the Al-Si alloy. Manganese mainly modifies the Al-Fe-Si phase and thus improves the ductility and shrinkage characteristics of the alloy. Nickel can enhance Al-Si alloy's strength and hardness at elevated temperature when combined with copper. Zinc improves heat treatment but may produce shrinkage. Lead improves machinability. Phosphorus refines primary silicon phase in hypereutectic alloy. Formation of second-phase precipitates, influence on porosity, grain refinement, and phase modification are the major mechanisms responsible for the effects of alloying elements on the properties of Al-Si alloy.

A good alloying example is the so-called 3HA alloy. The typical composition is Al-14Si-2Cu-0.5Mg-0.5Mn-0.05Zr with 0.05% strontium used as the modifier. This alloy has been reported to have a unique combination of good machinability, improved high temperature strength, wear resistance, corrosion resistance, and fluidity, thus becoming an alternative Al-Si alloy that can be used to make lineless engine block.[14-17]

4.2 Production of Al-Si Alloy Based Composite

4.2.1 Hard Secondary Phase Reinforced Composite. Based on the effects of hard precipitates on the Al-Si alloy, aluminum-based composite reinforced with hard secondary particles/fibers has been a hot research topic for a long time. In such a composite, some hard ceramic particles/fibers are processed into the matrix to enhance the material's hardness and thus affect fatigue behavior and wear performance as well. SiC and Al_2O_3 are the most common reinforcing ceramics for Al-Si alloys.

The high cycle fatigue behavior in a hypoeutectic A356 Al and hypereutectic A390 Al reinforced with two sources of SiC whiskers has been recently studied.[18] A 17 vol.% of SiC whiskers were randomly embedded into the Al-Si matrix by squeeze casting. The addition of SiC whiskers in the A356 alloy matrix increased the fatigue strength at 10^7 cycles by 29-40% while in the A390 Al by only 3-20%. This difference in the fatigue strength improvement is attributed to the higher fraction of brittle silicon phase in A390 Al, whose breaking somewhat offsets the reinforcement from the hard whiskers. Figure 7 shows the major microcrack initiation sites in these composites. The reinforcement free region in the composite is the first microcrack initiation site for both hypoeutectic A356 Al and hypereutectic A390 Al matrix composite. Further studies found that in A356 Al matrix composite, the slip is the main mechanism for the microcrack initiation at the reinforcement free region, while in A390 Al matrix composite, the breaking of silicon particles is responsible for the microcrack initiation in the reinforcement free region.

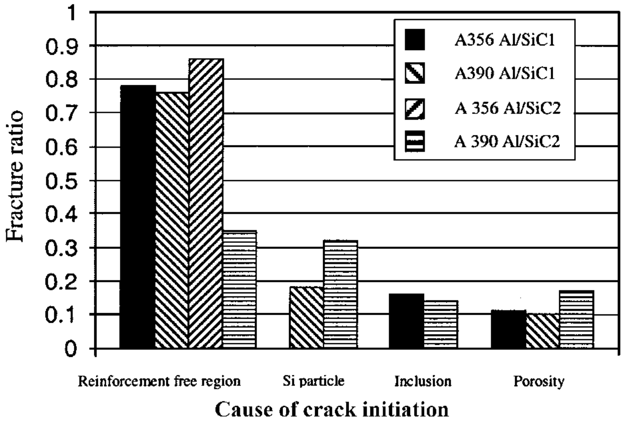

Fig. 7 The microcrack initiation sites in A356 and A390 Al-Si matrix composite

The high volume of hard phase in the matrix also increases the composite's wear resistance. For better wear resistance, the volume fraction of SiC particle can be as high as 60%,[19] although it makes the material hard to machine. With respect to the machinability, the low volume fraction of the hard secondary phase particles/fibers reinforced composites shows a better application potential. An addition of low fraction of SiC (2~8 vol.%) particles to an Al-12 wt.% Si alloy has been found to raise the wear resistance significantly [20]. Figure 8 shows the enhancement of the wear resistance of the Al-12 wt.% Si alloy by adding 6 vol.% SiC particles and the wear resistance of the composite continues to increase among all the tested SiC fractions. Accompanying this significant increase in the wear resistance is only a slight increase in the material's macrohardness. At 8 vol.% SiC fraction, the macrohardness is only 112 HV while the non-reinforced Al-12 wt.% Si alloy itself has a macrohardness value of 103 HV. This minor increase in hardness permits an efficient machining of this material.

4.2.2 Soft Secondary Phase Reinforced Composite. Compared with the hard phase reinforced composite, where high hardness is the objective, some soft particles/fibers are also used to reinforce the Al-Si alloy. The most commonly used soft phases are graphite and MoS_2. The major objective in this case is to reduce friction of the alloy with the counterpart, and thus diminish wear loss. A eutectic Al-11.8Si-3Mg alloy has been added with 5% graphite and experienced squeeze casting. The density and ultimate tensile strength (UTS) of the final composite casting were increased from 2.63 to 2.67 g · cm^{-3} and from 75 to 145 mN · m^{-2}, respectively. Moreover, both the primary α and eutectic silicon are refined owing to the enhanced heat transfer.[21] In another study, the graphite fraction was increased to 20 wt.%.[22] It has been noticed that primary silicon preferentially grains on the graphite particles and no significant chemical reaction is observed between the interface of graphite particle and matrix. The hardness, friction coefficient, and wear loss of the composites with respect to the graphite content are shown in Fig. 9, 10, and 11, respectively. Figure 9 shows that the hardness of the composite decreased with increasing graphite content, and the hypereutectic alloy

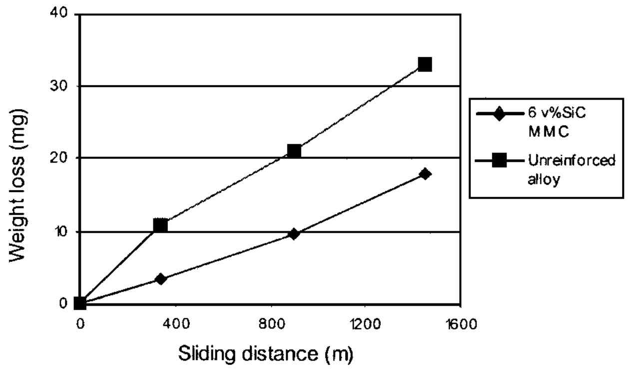

Fig. 8 The effects of low fraction SiC particles on wear loss of Al-Si alloy

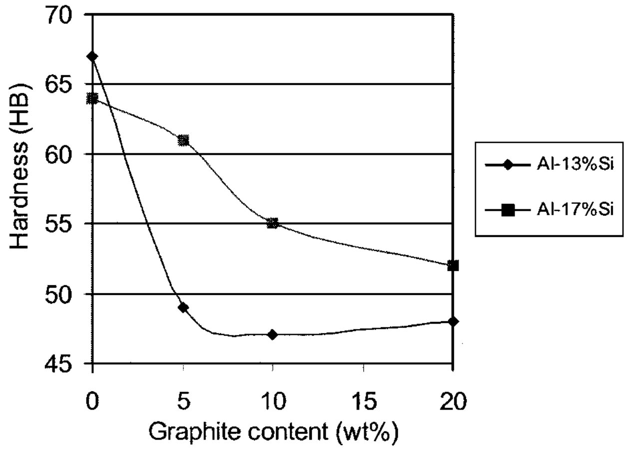

Fig. 9 The hardness and graphite content in Al-Si alloy

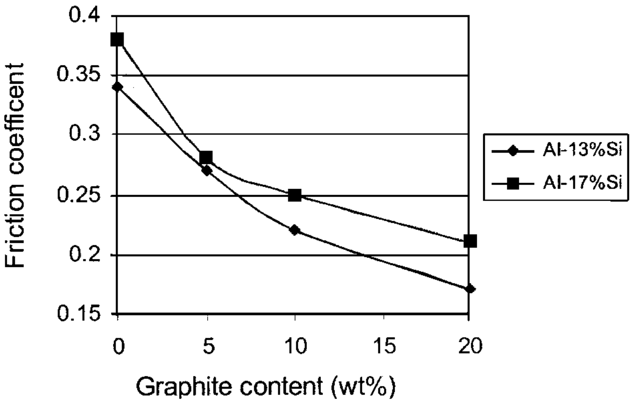

Fig. 10 The friction coefficient and graphite content in Al-Si alloy

exhibits a higher hardness with the higher fraction of silicon. Figure 10 shows that the friction coefficient of the composite decreases with the increase in the graphite content and Al-17 wt.% Si has a lower friction coefficient from the higher silicon content, which has a lower friction coefficient with metal. Figure 11 shows a minimum wear rate of the composite at the fraction of 5 wt.% of the graphite. This is because below 5 wt.%, the increase in the graphite decreases the friction and above this content, graphite reduces the strength of the material more than the friction coefficient. Thus the final result is the reduction in the material's wear resistance. Successful applications of graphite reinforced Al-Si alloy in engines have been reported.[23]

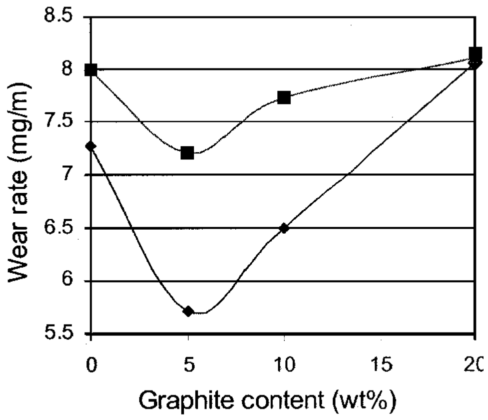

Fig. 11 The wear rate and graphite content in Al-Si alloy

4.2.3 Hybrid Secondary Phase Reinforced Composite. Combining the design guide of hard and soft secondary phase reinforced composites, hybrid second phase reinforced Al-Si alloy has been reported. Roy et al.[24] found that the composites containing SiC, TiC, TiB_2, or B_4C particles exhibit a lower wear rate when compared with the base metal. However, the aluminum alloy base composite not only contains the hard particles but also graphite has the lowest wear rate because it is not only soft but also shears easily along the base plane of its hexagonal close packed lattice in a suitable environment and acts as a solid lubricant.

The hybrid second phase reinforced Al-Si alloy has been introduced to make engine block. An Al-12 wt.% Si alloy matrix composite has been developed by reinforcing the Al-12 wt.% Si alloy with 17 vol.% short alumina and 7 vol.% carbon fibers.[25] A real engine block is manufactured with such a composite. Some friction and wear data are obtained from road tests on actual vehicles. Figure 12 and 13 compare friction and wear test with cast-iron lined block engine, respectively. The friction coefficient in the composite block stays at a low level among all the test stresses while the cast iron engine block has a much higher friction coefficient when the test stress is over 20 MPa. The wear resistance of the composite block is also superior, even lower than that of the cast iron liner engine block.

4.3 Melting, Casting, and Heat Treatment Techniques

Since the microstructure of a material greatly relies on its processing, a lot of progress is being made in the field of aluminum alloy, from its melting to heat treatment.

4.3.1 Melting. Currently, some new melting techniques are being studied for aluminum alloy. Electron beam surface melting has been used to melt and characterize the phase content formed in 1200 Al alloys and produce a qualitative solidification microstructure selection map.[26] Aluminum alloys can also be melted using a plasma arc direct current furnace for

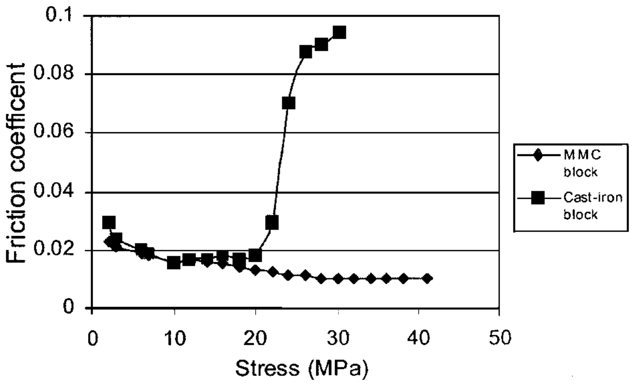

Fig. 12 Friction coefficient of Al-Si matrix composite and cast-iron engine block

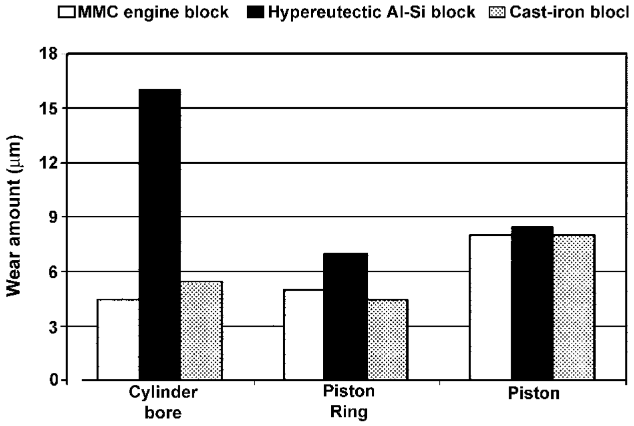

Fig. 13 The wear comparison in the MMC and cast-iron engine

analyzing the thermal, physical, and chemical processes occurring during the heating of aluminum alloys.[27] Plasma direct current arc can lead to alloy degassing, decreasing of intensity of oxidizing processes, and refining during melting process.[27] When melted in high vacuum of 2×10^{-7} Pa for 2 h using a cold-crucible induction furnace, a metallic luster is found on the surface and a large number of highly perfect Al crystals are found inside the as-melted ingot. Purity of the melted Al was estimated to be ~99.9999%.[28]

In addition to the new melting techniques, studies are still actively examining cleaning and degassing, and physical and chemical reaction kinetics in melt, as casting defect, phase morphology, and grain size all greatly depend on these factors. For instance, the Al-9 wt.% Si-3 wt.% Cu sample quickly solidified from melt of a low hydrogen level, 0.06 mL/100 g Al, exhibited almost no pores while a higher hydrogen content in the melt or a lower solidification rate at the same melt hydrogen content produced a significant porosity in the final casting.[6]

4.3.1.1 Cleaning and Degassing. To more precisely control hydrogen and oxide content in aluminum melt, kinetics of hydrogen dissolution and aluminum oxidation in molten aluminum has recently become an active research topic. Degassing and reabsorption of refined aluminum melt have been studied and the kinetic models of hydrogen atoms have been established.[29] In a study of the oxidation kinetics of Al-Si melts by air oxygen, it was found that the oxidation process of liquid alloys adheres to parabolic law.[30] Non-metallic inclusion is removed and separated as a function of fluxing gas flow rates, chlorine concentration, and stirring energy and found a two-step removal mechanism of non-metallic inclusions.[31] Oxidation kinetics of Sr, Na in Al-Si melt in modification has been investigated.[32] With the results of hydrogen determination in aluminum melt, Ref. 33 discusses heredity of hydrogen in aluminum alloy and the effects of cooling rate and melting condition on the heredity.

New cleaning and degassing techniques are another active research area in Al alloy melting. Reference 34 reports an examination of common methods such as vacuum processing, electric flux refining, argon blowing of the melt, argon-chlorine (1-5%) blowing of the melt with high speed of gas flow, ladle cleaning from impurities and particles of aluminum melt degassing, and a proposed new gas mixer with porous parts for the argon blowing of the melt. Reference 35 reviews the practice of purging inert gas bubbles through molten aluminum alloy to remove hydrogen gas and discusses porous refractory diffusers with fine pore size, a low-cost equipment to effectively degas molten aluminum.

4.3.1.2 Grain Refinement and Phase Modification. As discussed above, the coarse grains and silicon particles are very detrimental to the mechanical properties of Al-Si alloy. Microstructure refinement in melting is achieved by controlling melt chemistry such as grain refinement and eutectic modification. Kinetics of grain and silicon particle growth and new master alloy development are the major areas for current research. Zhang et al. studied the dissolution process of primary silicon particles in Al-18 wt.% Si alloy and established a dissolution model of primary silicon in the melt.[36] Reference 37 discusses present development and application of masteralloy refiners in aluminum alloys with a highlight on AlTiBRE, a new masteralloy of high and long-term efficient grain refining effect which is better than that of Al_5TiB refiner. Reference 38 also reports new masteralloys Al-(1-5)% Sr and Al-12% Si-(1-5)% Sr and their high modifying ability for hypoeutectic Al-Si alloy.

Studies have also shown that, in addition to adding grain refiner, low superheat pouring is an alternative to grain refinement. However, compared with the columnar or equiaxed dendritic structure induced by grain refiner, low superheating usually produces rosette-like or non-dendritic grain morphologies.[39,40]

4.3.2 Casting. The Al-Si alloy engine parts are usually formed by casting. A good casting is supposed to fill the mold cavity without defects. Thus, the gating system design, cooling rate, and casting pressure can all affect the as-cast structure.

The refinement of structure can often be achieved by controlling casting process parameters. Cooling rate is important in the formation of microporosity. Higher cooling rate reduces solidification time and the grain size of casting. With a higher cooling rate, grain density increases, dendrite arm spacing decreases, and the average pore size decreases. With a lower cooling rate, more gas can precipitate from the melt and thus produce higher porosity. Therefore, for a given hydrogen level, the percent porosity, pore length, and pore area are all increased with a longer local solidification time. Accordingly, cooling rate of the casting is normally used to control the

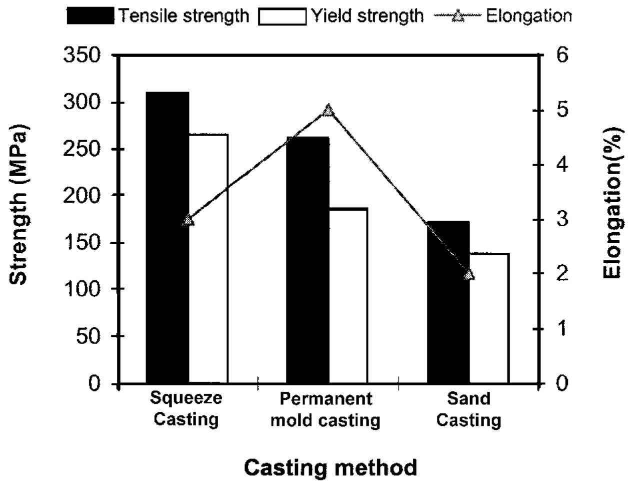

Fig. 14 The mechanical properties of 356 alloy by different castings

microstructure and thus change the fatigue and wear behavior of Al-Si alloy. In addition to cooling rate, pressure on the melt during the solidification is another processing parameter that can be controlled to improve casting microstructure. External pressure can improve feeding ability of molten alloys so that the porosity can be reduced by introduction of pressure during solidification.

Currently, apart from conventional casting processes such as sand casting, permanent casting, and die casting, some other new casting techniques have been developed for Al alloys. Semi-solid processing, squeeze casting, and Cosworth process are typical examples of this kind of new technique.

In conventional casting, the primary dendrites normally grow and interact with each other. As a result, when only small amount of the melt (20%) freeze, viscosity of the melt increases rapidly and fluidity drops drastically. However, in semi-solid processing, the dendrites are broken by vigorous agitation during the solidification, and reasonable fluidity of the melt can be maintained until the solid content reaches as much as 60%. In addition, each broken dendrite becomes a separate crystal and this refines the grains without the addition of grain refiner. In this process, shrinkage and cracking of the casting are reduced because the alloy is already partly solidified when cast. Another advantage of this process is that the composite castings can be easily produced by adding fibers or particles (compocast). The application of this technique is still in its early stage and some brake cylinders and pistons have been manufactured by this process.

Squeeze casting involves compressing the liquid metal in a hydraulic press during solidification, which effectively compensates for the natural solidification contraction. Under high pressure, the shrinkage can be filled and the entrapped gases can remain in the solution. Moreover, the heat transfer is also enhanced due to a closer contact between the casting and mold walls and thus the cooling rate is increased. The casting thus produced by this process has a higher strength. A comparison of the mechanical properties of a cast 356 Al alloy (T6 treatment) has shown the significant improvement of its strength by squeeze casting over permanent mold and sand castings (Fig. 14).[1] A study about a 7010 alloy found squeeze casting produces a fatigue resistance of the casting that is even comparable with that of the wrought alloy (Fig. 15).[41] This technique can also be readily used to cast metal matrix composite and aluminum alloy car pistons are now being manufactured by this process commercially.

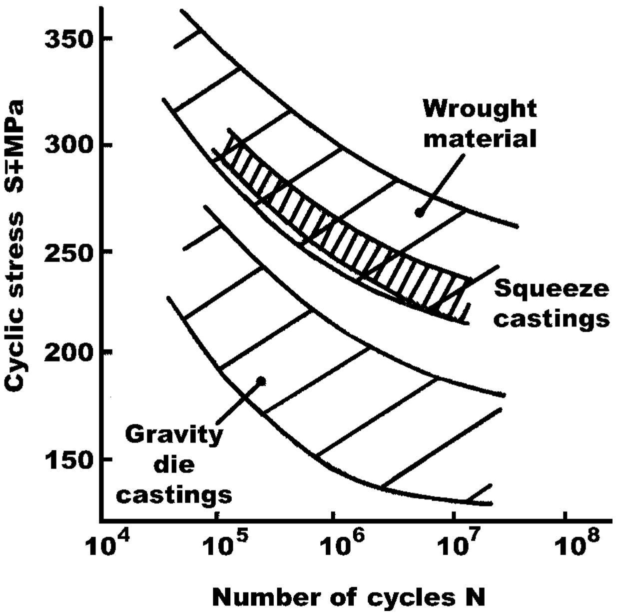

Fig. 15 The fatigue properties of 7071 alloy produced in different methods

Since oxide and other inclusions are detrimental to the mechanical property of castings, the Cosworth process was invented to quiescently transfer the aluminum alloy melt into the mold and thus avoid the formation of any inclusions and/or entrapped gases by the turbulence occurring in the conventional casting process. In this process, the aluminum alloy melt is held in a furnace with protective atmosphere and thus no fluxes or chemicals are used. Accordingly, the generation and entrapment of oxide particles is minimized and porosity is also reduced compared with the conventional casting process. Some thin-walled and pressure-tight components have been cast by this technique, and engine head is one of these examples.

4.3.3 Post-Casting Treatment

4.3.3.1 Heat Treatment. For Al-Si alloy, heat treatment is used to increase strength or improve the ductility of the alloy. The heat treatment of the Al-Si alloy normally involves the precipitation of the hard secondary particles from the matrix to produce precipitate strengthening of the matrix. The alloying elements such as Mg, Cu, and Cr have a decreasing solubility in the Al matrix as the temperature drops (Fig. 1). The recent studies on the thermal treatment of Al alloy attempt to influence the precipitation reactions by adding some trace elements such as cadmium, indium and tin. The addition of these trace elements can modify the precipitation process and thus further strengthen the heat treatment effects. During the heat treatment of an Al-7Si-0.3Mg cast alloy, it has been found that trace additions of In, Cd, Sn, and Cu inhibit delayed aging. These elements, in decreasing order of effectiveness, are In, Cd, Sn, and Cu. The indium addition gives superior tensile strength, whereas the cadmium addition gives superior ductility.[42] The aging effects of major element such as Cu, Mg, and Cr have been studied often while the influences of these trace elements have not.

Some other current studies on aluminum alloy heat treatment are microstructure control of materials and relationship between alloy chemical composition, heat treatment process, alloy structure, and alloy properties.[43-48]

4.3.3.2 Hipping. Recently, hot isostatic pressing (hipping) has been used to treat porosity and nonmetallic inclusions in castings. During hipping process, the casting is set in a closed space and heated to a temperature under a particular pressure from an external gas. The hipping temperature is usually greater than 0.7 of the melting point of the hipped material.[49] This relatively high temperature during the hipping is necessary to lower the yield strength and to raise plastic flow of material sufficiently for pore closure to happen in a reasonable time. The external gas pressure developed during the hipping cycle is achieved partially by the mechanical compressor and partially by the heating of the gas in the closed space.

Hipping can remove both macro- and micro-porosity. Under hipping conditions, considerable creep of metal occurs and during the final stage of hipping densification, the surfaces of the pores are pushed together to form bonding between the surfaces because atoms diffuse in both directions across the interface.

In addition to the removal of porosity, hipping treatment can also influence nonmetallic inclusions. After the hipping treatment, some oxides in the Al-7Si-Mg alloy were found to be bonded between each other and the structure of the oxide was also changed.[50] Thus the hipping process can reduce porosity and strengthen some inclusions and thus increase both fatigue and wear resistance of Al-Si alloy and Al-Si matrix composite.

5. Summary

The fatigue and wear properties of Al-Si alloy are discussed. The silicon phase is important to both of these properties. Coarse silicon usually reduces fatigue life due to microcrack initiation. Higher silicon content usually increases the wear resistance of Al-Si alloy as it increases the alloy's hardness. Intermetallic precipitates and casting defects also influence fatigue and wear performance. Fine precipitates can usually strengthen the alloy while sharp and coarse precipitates degrade these two properties. Casting defects such as porosity and inclusion usually reduce the alloy's fatigue and wear resistance due to microcrack initiation.

Alloying elements can form fine precipitates, refine grain size, modify silicon phase morphology, and reduce the effects of defects and thus can usually increase both fatigue and wear resistance. Composite is another way to improve Al-Si alloy's properties. Both hard and soft phases are used to reinforce Al-Si alloy and enhance its fatigue and wear resistance.

New processing techniques such as semi-solid processing, squeeze casting, and Cosworth process are being developed to remove casting defect and improve Al-Si alloy's microstructure and increase its properties.

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