Review of Hypereutectic Al-Si Alloy Microstructure Refinement Methods and Wear Characterization Studies

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Abstract – Hypereutectic aluminum-silicon alloys have widespread use in automotive engines due to their high silicon content which provides enhanced tribological and mechanical properties suitable for engine operation. This review paper attempts to understand various microstructure refinement methods adopted in order to improve wear characteristics and mechanical properties of the alloy. These refinements have proved to reduce Si particle size which decreases frictional losses, enhances hardness and improves the thermal stability of the alloy. Such structural changes help make automotive engines more efficient and durable.

Keywords: **Hypereutectic; Al-Si; Tribology; Wear; Microstructure;**

INTRODUCTION

Aluminum-silicon alloys have found extensive application in automotive engines due to their benefits over conventional cast iron engines which are now near obsolete. Silicon being harder than aluminum, when used together with high silicon content i.e. Si greater than 20wt%, enhances the mechanical properties [1], [2] including hardness, wear resistance etc of the otherwise softer aluminum improving its mechanical characteristics and making it more suitable for automotive engine usage. Automotive engines are subjected to sliding wear between the piston and cylinder surface. Therefore, it is important to study the wear characteristics of the alloy. It has been found that mechanical properties of the alloy are a function of its microstructure, shape, and size of Si particles in the primary Si phase[3], [4], [5].

1.1 Classification

Based on the composition of Si, Al-Si alloys are categorized into 3 types namely – Hypoeutectic possessing <12wt%Si, Eutectic alloy with 12wt%Si and Hypereutectic type possessing >12wt%Si. Among these, the hypereutectic type alloys have better wear resistance as compared to the other types due to higher hard silicon content present in the alloy.

1.2 Problem Statement

A major drawback of using hypereutectic Al-Si alloys is the formation of large Si particles in the primary Si phase due to low cooling rates or poor solidification conditions[1], [6], [7], [8], [9]. During sliding wear, the soft Al wears out quickly as compared to the much harder Si, leading to exposure of large Si at the surface[10]. These large particles promote pull-out of Si and also become a source of crack initiation which is unfavorable [1], [4], [11].

This review paper focuses on the various methods adopted to refine the microstructure which in corollary enhances the wear resistance and other mechanical properties such as UTS, hardness, percentage elongation etc. of the alloy.

which contain 20% or more silicon by weight. Silicon has high hardness and therefore the silicon particles projecting out of the soft aluminum at the surface offer themselves as contact points for sliding and resist wear. Also, the gaps between these particles retain an oil film offering minimum friction[12], [13]. Aluminum cannot dissolve more than 12%

REFINEMENT METHODS

1.3 Refiners, modifiers and Rare Earth Metals

There have been various attempts to add rare earth metals such as samarium, cerium and lanthanum to modify the hypereutectic silicon phase and enhance the material properties. Bo & E investigated the effects of P and RE addition and observed that that P refines the primary Si and RE mainly modifies the eutectic silicon phase from large needle-like to fine fibrous or lamella type structures[14]. Alkahtani reported the individual and combined effects of Lanthanum(La) and Cerium(Ce) and a noticeable microstructure refinement was achieved at earth metal concentration above 1.5wt%[15].

Optical microscopy and SEM investigations on Samarium addition reported an effective refinement of α(Al) dendrites and eutectic silicon from plate like to needle-like phase was achieved with improved mechanical properties[16]. The combined use of modifier Phosphorous and rare earth metal, Cerium (Ce) resulted in microstructure refinement from needle-like Si to short or fibrous type enhancing alloy mechanical properties[2].

Several authors have investigated the use of refiners and modifiers to improve alloy performance through microstructure refinement and also improve the wear resistance of the alloy. SEM/EDX microanalysis on worn surfaces of Al-Ti-B based grain refined hypoeutectic and eutectic AL-Si alloys of different compositions showed improved wear resistance, mechanical and tribological properties with refined Si phase from plate-like to fine particles[17] [18]. The use of ZrB2 composites showed increased hardness, reduced grain size and enhanced tensile properties[19].

Strontium addition at higher cooling rates significantly improve elongation and ultimate tensile strength, and ductility of the alloy and spheroidization of Si particle morphology was achieved in Al-6Si hypoeutectic alloy [20]. Mn addition causes good strengthening properties in hypereutectic alloy[21].It was confirmed that wear behavior is greatly influenced by the size of Si phase. Combined refined and modified hypereutectic alloys were investigated for dry sliding wear behavior A uniformly distributed primary Si phase was obtained in case of combined refined and modified samples and these structural changes attributed to improvement in wear resistance of alloy[5].

1.4 Melt Treatment

1.4.1 Melt temperature modification:

Cooling and solidification rates are crucial in microstructure formation and preserve heterogeneities. It was observed that by melt overheating the alloy tends to be less sensitive to cooling and solidification rates. Hence, heterogeneities are removed and a refined microstructure is obtained[6]. Microstructure evaluation shows that increasing the cooling rate and superheat temperature decreases primary Si precipitation and volume fraction, and morphology changes from dendritic and octahedral facetted to plate-like structures[22].

It was concluded that higher cooling rates promote smaller Si formation and at low cooling rates Si particles combine to form large globules of Si in the matrix[9]. It was observed that with increasing Si content, the yield point of alloy increases[23] and microhardness and microstructure inhomogeneity increase as the particle size decreases gradually transforming from irregular to quasi-spherical shape[7].

1.4.2 Melt stirring:

It was observed that stirring speed has a significant effect on the refinement of primary Si particles and lower wear rates were observed for stir cast as compared to conventional cast Al-Si[24]. By increasing the number of passes, the Si grain size and aspect ratio decreases[25]. Cooling and solidification rates studies conclude that Si morphology transforms to fine block shape and a smaller eutectic Si phase with an average particle size of 2µm is achieved through rapid solidification of melt stirred hypereutectic alloy [26]

1.4.3 Ultrasonic melt treatment:

It was observed through an optical microscope that ultrasonic wave reduced hydrogen bubbles in the hypereutectic melt, significantly refining primary Si phase while in the liquid phase with α-Al transforming from dendrite to equiaxed crystals[27] and coarsening occurs on further solidification of the alloy[28].Addition of ultrasonically treated melt to untreated melt enhanced the roundness and aspect ratio of the alloy improving wear resistance and tensile strength[29].

An attempt was made to study the individual and combined effects of melt stirring and ultrasonic melt treatment of hypereutectic alloy. Effective primary Si refinement was achieved in case of Ultrasonic treated samples as a result of particle collision and shock waves that changes eutectic morphology leading to improvements in mechanical properties[30].

1.4.4 Combined methods:

Robles Hernandez et al studied the combined effects of ESV and chemical modifiers such as P and Sr at a range of temperatures above melt liquidus temperature. Combination of ESV and chemical treatment reduces Si particle size and microstructure refinement was achieved in hypereutectic Al-Si alloy[31]. Another study on the influence of electronic melt vibration with the addition of AlCuP and argon gas bubbling of the melt conducted by Yeom et al resulted in refined Si phase and a significant improvement in tensile, impact, hardness and ductile fracture properties[32].

1.5 Pulsed rapid cooling

The nanostructure formation mechanism of hypereutectic Al-Si alloy produced through rapid solidification by means of the pulsed electron beam was studied. It was found that by increasing the number of pulses, the Si elements diffuse and refinement of microstructure was achieved with fine dispersive nanosized spherical Si crystals[33]. Subsurface erosion and melting were observed at high cathode potentials. However, dry sliding wear tests suggest an improved dynamic friction coefficient as a result of oxidative tribofilm formation and increased surface roughness over untreated samples[34].

Investigations were carried out to study the microstructure and Vickers's hardness of fine Si particles sintered in hypereutectic Al-Si alloy. It was observed that the size of Si remained at the submicron level and hardness of sintered alloy was two to three times higher than the conventional alloy of same composition[35].However, in case of laser cladding, formation of large Si particles was observed by decreasing laser power and increasing powder feed rate[36] Zhao et al observed that increasing the laser power and scan speed increases the volume fraction and decreases the size of Si particles also enhancing the microhardness of the alloy[37].

The effects of laser treatment on wear behavior and microstructure for hypereutectic Al-Si were studied. It was noted that laser power has a strong influence, due to increase in solidification time, large size Si particles are formed resulting in poor wear resistance The use of SLM has observed lower wear rates and high microhardness of Al-Si alloys as a result, controlled microstructures and mechanical properties can be obtained[38]. Higher laser powers exhibit larger and more irregular Si phase. However, the microstructure studies reveal the SLM processed samples show much refined Si phase as compared to conventionally casted alloys. Wear studies conclude that an ultrafine microstructure with large Si phase enhances wear resistance in the samples which predominantly exhibit abrasive and oxidative wear[39].

WEAR STUDIES

Wear studies suggest that transition load for dry sliding wear can be increased by, increasing the Si content, increase in hardness and by decreasing the silicon particle aspect ratio. The decrease in silicon particle size had the most significant effect on the wear coefficient[40]. A fine Si phase increases the surface area and promotes an even distribution of load thereby improving wear resistance. Wear track microstructure results exhibit material loss, fragmentation, sinking of Si in Al matrix due to void formations in the alloy[13]. Prasad et al conclude that refinement of primary Si phase improves mechanical properties, exhibits better wear resistance, reduces the tendency of microcracking, improves thermal stability, enhances alloy hardness but negatively affects tensile strength. Mechanical properties and tribology are mainly influenced by shape, size, microcracking tendency and thermal stability of the alloy[4].

Uniformly dispersed fine Si particles act as a solid lubricant even against dry sliding conditions[41] [42] Small and well dispersed Si phase avoids abrasive wear thereby improving wear resistance[43]. Alloys with low Si particle fraction exhibit high amounts of wear due to the erosion of softer aluminum. Large Si particles accelerated the wear by cracking and fracture of large Si particles[10] Higher Si content promotes Si particle pull-out leading to three-body abrasive wear resulting in poorer wear resistance[1]

Wear tests were conducted using a pin on disc wear tester for different compositions of hypereutectic Al-Si alloys under dry and lubricated conditions characterized using techniques such as Optical Profilometry and Electron Microscopy. It was observed in case of boundary lubricated alloys, a formation of oil layer reduced abrasive wear for sliding at high cycles and suggest dominant wear of Al matrix after Si particles were completely worn out[44].These tribofilms act as energy absorbers, resist crack propagation and promotes chipping fracture of silicon at higher loads[11].

CONCLUSIONS

As observed in the various studies, the following conclusions can be listed as follows:

- Tribological enhancements can be achieved through microstructural refinement.
- Solidification conditions and cooling rates critically influence size and morphology of primary Si phase. At faster cooling rates, a refined microstructure with fine Si is obtained.
- Wear characteristics of hypereutectic alloys are a function of primary Si phase size and shape.
- Overheating of melt reduces the sensitivity of melt alloy to cooling and solidification rates.
- Modified hypereutectic alloys with smaller and finer primary Si phase exhibit better wear resistance as compared to conventional alloys with the same composition due to uniform distribution of load on the increased surface area of Si phase.
- Microstructure refinement improves the microhardness of the alloy. Results also exhibit an improvement in thermal stability, ultimate tensile strength at lower and elevated temperatures.
- Plate-like and fibrous Si structures are more favorable than octahedral and dendrite structures.

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