A Review on the Effects of Casting Quality, Microstructure and Mechanical Properties of Cast Al-Si-0.3Mg Alloy

S. NALLUSAMY

Dean, Department of Mechanical Engineering, Dr. M. G. R. Educational and Research Institute University, Chennai, 600095, Tamilnadu, India

(Received on September 26, 2015, Revised on December 08, 2015)

Abstract: This paper investigates a study on the effects of heat treatment on the microstructure, quality of casting and mechanical properties of Al-7Si-0.3Mg (LM25) alloy. The large reputation of Al-7Si-0.3Mg (LM25) alloy in automobile industry stems from its light weight (density of about 2.68 g/cc), high strength to weight ratio, excellent casting characteristics, high corrosion resistance, low coefficient of thermal expansion, good thermal & electrical conductivity and good mechanical properties including high machinability and workability. The microstructure of this alloy depends strongly on its composition and solidification rate. The slow-cooling rates encountered in sand castings lead to acicular silicon phase. The silicon phase in the form of large plates with sharp sides and edges act as internal stress risers in the microstructure and provide easy paths for fracture leading to inferior mechanical properties. The applications of this alloy demand several techniques and research methodologies to modify the microstructure and there by improve mechanical properties. Alloying, chemical modification, mould vibration during solidification and heat treatment were found to be effective in modifying the microstructure. In this view, this article presents the information’s about the influences of all such techniques which modify the microstructure and increase the quality of casting and mechanical properties.

Keywords: Heat Treatment, Microstructure, Mechanical Properties, LM25 Alloy, Vibration, SEM

1. Introduction

The review of literature reports a number of studies on mechanical properties of Al-7Si-0.3Mg (LM25) alloy. Hypoeutectic Alloys in the Al-Si-Mg system normally contain 7% Si and 0.2-0.6 % Mg. The Al-7Si-0.3Mg Alloy is a hypoeutectic alloy. This is gaining widespread popularity and finds applications in automobile, aerospace and marine engineering industries due to its excellent combination of properties such as low density, good fluidity, low coefficient of thermal expansion, high strength-to-weight ratio and good corrosion resistance [1,2]. Its potential uses are increased by its availability in different conditions of heat treatment viz., Precipitation treated, Solution treated, Solution treated and stabilized and fully treated conditions. The microstructure of the LM25 alloy consists of dendritic primary Aluminium and platelet eutectic Si. The typical microstructure of an unmodified LM25 Alloy is shown in figure 1. The mechanical properties of this alloy are greatly influenced by the morphology of Si phase. Si is polyhedral in shape and eutectic silicon is coarse acicular in shape. Presence of coarse acicular shape is detrimental as needles act as internal stress risers and lead to premature failure. It is well established that...
chemical treatment of the alloy called modification results in transformation of Si morphology and subsequent improvement in mechanical properties [3, 4].

The modification of eutectic Si can also be achieved by other methods like rapid solidification, mould vibration and melt agitation. Na, Sr, Ca & Sb found to result in good modification in hypoeutectic Al-Si alloys. Grain refinement refers to the development of increased number of sites for the nucleation of primary alpha Aluminium phase during solidification of the casting, which results in fine equi-axed structure throughout the material and ensures uniform mechanical properties [5-8]. Cast Al-Si-Mg alloys can be heat treated to obtain optimum combination of strength and ductility [9 & 10].

![Aluminium Unmodified Dendrite](image1) ![Eutectic Silicon](image2) ![Silicon Flakes](image3)

(a) Optical Micrograph (x120) (b) Scanning Electron Micrograph

**Figure 1:** Typical Unmodified Flake Microstructure of Cast Al-7Si Alloy [11]

2. Literature Review

Li et al. [11] investigated the effects of ytterbium (Yb) on the microstructure and eutectic solidification behaviour of Al-7.5%Si-0.45%Mg alloys. The micro-structural observations show that the addition of Yb causes a structural transformation of eutectic silicon from a coarse plate to a fine flake-like and some branched morphology. Zhang et al. [12] reported that the Sc addition in varying proportion to Al-7% Si alloys, modify the microstructure of the eutectic Si from a coarse, plate-like and acicular to a finely branched and fibrous pattern. The effects of La addition on the microstructure and tensile properties of B-refined and Sr-modified Al-11Si-1.5Cu0.3Mg casting were investigated by Tao Lu et al. [13]. The effects of Sr and Mn additions, cooling rate, and a range of aging temperatures and times on the impact toughness of a near-eutectic Al-11%Si-2.5%Cu-0.3%Mg-0.45%Fe alloy were investigated by O. Elsebaie et al [14], using unnotched samples in order to emphasize the role of metallurgical parameters on both crack initiation and crack propagation processes. Alloy toughness is one of the more important mechanical properties to consider in the case of critical automotive components. It may be defined as a measure of the ability of a material to absorb energy up to the point of fracture. An ideal grain refiner has been designed for Al-7Si alloy by performing sensitivity analysis of trained artificial neural network (ANN) model by N. S. Reddy et al [15].

An artificial neural networks model has been developed for solving these complex grain refinement phenomena in Al-7Si alloy. The model predictions and the analysis are well in agreement with the experimental results and existing metallurgical facts. Shamusuzzoha [16] revealed that the dual refinement of the primary and eutectic silicon
phases in shape casting of hypereutectic AlSi alloys is possible with Ba metal addition. Zuo et al. [17] investigated the effect of rapid solidification on the microstructure and refining performance of an Al-18Si-2.5P master alloy. The results show that as the solidification rate increases, the size of alkaline phosphatase particles in Al-18Si-2.5P master alloy reduces and the morphology of alkaline phosphatase evolves from plate-like to the fine nodular shape. Shin et al. [18] investigated the effect of Sr addition on the microstructure and mechanical properties of Al-10.5Si-2.0Cu recycled diecasting alloy. The addition of Sr of the order 0.01-0.02 wt% in the Al-10.5Si-2.0Cu recycled alloy transformed the morphology of the eutectic Si from an acicular shape to lamellar. Booth-Morrison et al. [19] revealed the effect of substituting 0.01 or 0.02 % Er for Sc in an Al-0.06 Zr-0.06 Sc % alloy to develop cost effective high-temperature aluminum alloys for aerospace and automotive applications Weixi et al. [20] and Xu et al. [21] reported that with the Nd addition in hypereutectic Al-15 wt% Si alloy, the morphologies of primary silicon changes from coarse blocky shape and irregular morphology (20-40 μm) to fine blocky shape, with primary silicon size reducing to 10-20 μm. Zhang et al. [22] studied the effects of barium modifier content on the mechanical properties, microstructures, and wear resistance of Al-Mg-Si alloys at room temperature. The Ba modifier at 1 wt% exhibited the best results for the mechanical properties of alloy. During a part of research a static and fatigue analysis of aluminum alloy wheel A356.0 was carried out using FEA package by S. Nallusamy [23]. The 3-D model was imported from CATIA into ANSYS using the appropriate format. Finite element analysis (FEA) is carried out by simulating the test conditions to analyze stress distribution and fatigue life of the aluminium alloy wheel rim of passenger car. Anil Kumar T et al [24] investigates the combined effect of the addition of 2% Al-5Ti-1B and electromagnetic induction with T6 heat treatment on the mechanical properties and wear properties of LM25 alloy casting. The mechanical properties assessed are hardness and ultimate tensile strength (UTS), microstructure examination, fracture analysis of the castings are studied. It is found that mechanical properties and wear properties of LM25 alloy have been considerably improved by subjecting the alloy to combined effect of the addition of 2% Al-5Ti-1B and electromagnetic induction with T6 heat treatment. A new mechanism of modification of eutectic silicon using Cd has been proposed by Prasada Rao and Mahfoud [25]. It has been found that Cd modifies of eutectic silicon in hypoeutectic Al-Si alloys. The modification effect increases with the increase in the addition level of Cd. Further, cadmium shows better modification effect at shorter holding time than at longer holding of the Cd containing melt of Al-7Si alloy.

3. Effect of Major Alloying Elements

The various alloying elements in Aluminium alloys are Silicon (Si), Copper (Cu), Magnesium (Mg), Manganese (Mn), Zinc (Zn), Lithium (Li), and Nickel (Ni). The major alloying elements in LM25 Aluminium alloy are Si and Mg. The effect of those two elements on properties of the alloy is discussed here.

3.1 Effect of Silicon (Si)

The addition of Silicon imparts excellent cast ability and resistance to hot tearing. Further, since Si increases in volume during solidification, the susceptibility of castings to shrinkage defects is reduced [26]. The density of aluminium is 2.7 g/cc and that of Si is 2.3 g/cc, hence Si is a favorable alloying element which can be added to aluminium
without losing the advantage of lightweight. However Si has low solubility in aluminum therefore precipitates as virtually pure Si which is hard and improve the abrasion resistance. Si reduces thermal expansion coefficient of Al-Si alloys. Machinability is poor with addition of silicon in aluminum.

3.2 Effect of Magnesium (Mg)

The presence of Mg in the alloy offers the ability to heat treat Al-Si castings to high strength levels. Mg combines with Si to form the age-hardening compound Mg2Si. In the as-cast state, Mg is present as fairly large particles of Mg2Si and hence has relatively little effect on the as cast properties of the alloy. Since Si levels are well in excess of the amount required to react with Mg, the degree of strengthening is determined by Mg content. Musa Yildirim et al. [26] have studied the effects of magnesium (Mg) addition to Al-7Si aluminum alloy in different amounts on the microstructure and mechanical properties.

Figure 2: Optical Micrograph of the Aged Al–Si–Mg (LM25) Alloy [26]

Three different alloys having various amounts of Mg (0.43, 0.67 and 0.86 wt. %) were prepared through casting process in the form of plates. All the samples were treated with aging process (T6) and then tensile samples were prepared from the homogenized samples Fe-rich inter metallic compounds, observed from the fracture surfaces were found to reduce the tensile strength of the alloy. T6 heat treatment was applied after the casting process to improve the properties of Al-Si-Mg alloys. Figure 2 gives the optical microscope images of Al-Si-Mg (LM25) alloys. The results also indicate that the tensile strength and hardness of the alloy increase with increasing Mg amount.

3.3 Effect of Microstructure Modifying Elements and Melt Treatment

The term ‘modification’ in Al-Si Alloys describes the change in the morphology of the eutectic silicon from a coarse-flake-like structure to a fibrous or fine flake structure. There are several variables which affect the evolution of microstructure as like type and quality of modifier, impurities in the melt, freezing rate, processing parameters and the Si content of the alloy etc. The addition of Na, Sr, Sb, Ca and rare earth elements is found to modify the coarse acicular morphology of Si into fibrous form. The effect of modification on phase diagram is shown in figure 3 before and after modification.
3.4 Effect of Sodium (Na)

Addition of Sodium in trace amounts causes a change in the solidification, morphological characteristics of silicon both in eutectic and primary form. Untreated alloy contains the silicon in the form of large plates with sharp sides and ends. The addition of small amounts of modifier like Na makes the eutectic silicon to solidify with a fine apparently globular morphology. The optimum amount of Na to be added into the melt is found to be in the range of 0.01-0.02% by weight [27]. The mechanism of modification and related facts were analyzed by many researchers. The process of modification is accompanied by an increase in both tensile strength and elongation. Re-melting of a modified alloy or holding the molten alloy for prolonged periods in the molten state results in a reversion to the unmodified condition. The addition of excessive amounts of sodium to the alloys can produce “over modification”. In this condition, alloy becomes susceptible to gas porosity.

3.5 Effect of Strontium (Sr)

Strontium is added as an Al-Sr or Al-Si-Sr master alloy which refines the Al–Si eutectic and results in castings having tensile properties comparable with those obtained when using sodium. It also changes the character of the eutectic from the irregular flake morphology to a pseudo regular fibrous morphology.

Figure 3: Phase Diagram of Al-Si Alloy System [27]

![Phase Diagram](image)

Figure 4: Typical Modified Fibrous Microstructure of Cast Al-7Si Treated with Sr [28]

![Microstructure Images](image)
The optimum amount of Sr to be added into Aluminum alloy melts is found to be 0.005-0.01% [28]. Pure strontium has sometimes been used as a modifier. But it is reactive with air and water vapour. Master alloys which contain less than about 45% Sr, are not reactive in air. Among sodium and strontium, sodium is a temporary modifier whereas strontium is a semi-permanent modifier. It means that effect of modification with sodium goes off on re-melting, whereas effect of modification with strontium retains even after repeated re-melting processes. Figure 4 shows the typical fibrous microstructure of modified LM25 Alloy.

3.6 **Effect of Calcium (Ca)**

Calcium, once considered only as a deleterious element because of its degrading effect on the properties of aluminum alloys, is now being considered to be a beneficial one in many ways. Ca introduced in the elemental form modifies the eutectic silicon in Al-Si alloys, improves the fracture toughness and impact properties of high iron containing aluminum alloys. The optimum amount of Ca to be added into aluminium alloys is found to be 0.04% by weight. The advantages of using Ca as a modifier are: Ca is easy to store and handle in the form of master alloy, over modification is not as serious as with Na, fully modified structure can be achieved. However it adds hydrogen to the melt and increases porosity [29].

3.7 **Effect of Antimony (Sb)**

Antimony can be added to eutectic or hypoeutectic aluminum silicon casting alloys to modify the morphology and microstructure of the eutectic silicon phase. Eutectic silicon solidifies in a relatively coarse continuous network of thin platelets and this morphology provides abundant stress risers and thus limits to achieve maximum strength and ductility. Modification with Sb is found to change the eutectic silicon into a fine fibrous or lamellar structure. The optimum amount of Sb to be added into aluminum alloy melt is found to be 0.10-0.15%. However the limitations with using Sb as a modifier are it forms poisonous SbH2 with hydrogen, unaffected by holding time and fully modified structure can never be achieved [25].

3.8 **Effect of Rare Earth Elements**

Rare earth elements such as La (Lanthanum), Ce (Cerium), Y (Yttrium), and MM (Misch metal) were reported to act as an effective modifier. Rare earth elements are used to modify Si phase from acicular needles to fibrous one and results in enhancing the tensile properties [30]. The Misch metal contained 50-52% Cerium, 20-22% Lanthanum, 15-17% neodymium and 10-12% of other rare earth elements. Based on experimental results, it was found that the addition of minor MM (≤ 0.2wt %) results in partial modification while more MM addition (0.3-0.1 wt. %) produce full modification. A higher percentage of Misch metal than sodium is needed for modification possibly because of the tendency of the modifying addition to react with the solvent phase thus inhibiting formation of stable silicon compounds. Misch metal addition increases under cooling up to 25 K with 0.2% addition giving rise to modified precipitate shapes. It forms inter metallic compounds Al4Ce, Al4LaAl2Ce, SiCe, SiCe2 etc. that suppresses growth of Si. Rare earth addition to Al-Si alloy is found to modify eutectic Si and improve mechanical property and gas porosity in LM25 is also reduced by addition of rare earth metals.
3.9 Melt Treatments

In addition to the modification, melt treatment techniques are commonly employed in the production of Aluminium Castings to control the porosity level, microstructure and to enhance the quality of casting [31].

3.9.1 Fluxing

There are different types of Chemical fluxes, which can be used for aluminium, have a number of functions. Covering fluxes form a molten layer to protect the melt from oxidation and hydrogen pick-up. Drossing-off fluxes agglomerate the oxides allowing easy removal from the surface of the melt. Cleaning fluxes remove non-metallics from the melt by trapping the oxide particles as they float out. Some Fluxes ‘modify’ the alloy, by introducing sodium, and improve its microstructure. Exothermic fluxes ensure that aluminium liquid trapped in the dross layer is returned to the melt. In general, the lower the melting points of the cover flux, the more efficient is its use. Coveral 11 fluxes is the most commonly used flux in most of the aluminium castings [31].

3.9.2 Degassing

In ordinary melting practices we can’t prevent complete gas absorption into the molten metal. But we can control the gas absorption by taking precautionary measures like using preheated charge, using dry tools, preheating the flux, degasser and grain refiner compounds. To remove the absorbed gases mainly hydrogen which is generated through decomposition of moisture, degassing operation has been carried out. In tablet degassing, the gas is introduced into the melt in solid pill form. The pills, added by a perforated bell, are composed of chemicals, which thermally decompose to release gas bubbles. The most popular solid degasser is hexachloromethane C2Cl6 (Degasser-190), which decomposes at temperatures above 700°C. Like all solid fluxes, these materials are hygroscopic and must be stored in a dry atmosphere; otherwise their use will add hydrogen to the melt rather than remove it. Tablet degassing is often quite suitable to the treatment of small melts and finds application where precise control of degassing is not required.

3.9.3 Grain Refining

Grain refinement refers to the development of an increased number of sites for the nucleation of the primary alpha aluminium phase during casting solidification. Samuel et al. [32] have investigated the influence of the addition of Ti and B in the form of five different grain refiners/aluminium master alloys (Al-10%Ti, Al- 5%Ti-1%B, Al-2.5%Ti-2.5%B, Al-1.7%Ti-1.4%B and Al-4%B) in conjunction with that of Sr (as modifier) added in the form of Al-10%Sr master alloy to A356.2 alloy. Grain refinement of an A356.2 alloy with Ti and B additions in the ranges of 0.02-0.5% and 0.01-0.5%, respectively, was examined using these different types of grain refiners. Tensile and impact tests were conducted to evaluate the influence of the interaction between grain refiner and modifier on the mechanical properties. The results indicate that individual additions of Ti and B up to 0.5%Ti and 0.5%B do not appear to modify eutectic Silicon. However addition of larger Boron content resulted in change of size of Si [33] and improved toughness.
4. Effect of Mould Vibration

Several researchers have investigated the effect of vibration on the microstructure of castings. The effects include promotion of nucleation and reduction in as-cast grain size, reducing shrinkage porosities due to improved metal feeding and producing a more homogenous metal structure. These improved features lead to enhanced mechanical properties and lower susceptibility to cracking. The effect of low frequency vibration on porosity of LM25 Alloy castings was studied and summarizes research into the effect of low frequency mechanical vibration on the porosity of unmodified and metallic sodium modified LM25 [Al-Si 7.15%] and LM6 [Al-Si 12.30%] alloys [34]. Vibration at varying frequencies between 15 and 41.7 Hz and amplitudes between 0.125 and 0.5 mm has been applied to both unmodified and metallic sodium modified LM6 and LM25 alloys during solidification. The results indicated that LM25 and LM6 alloys grain refined with Nucleant2 reduced the pore volume %. The amount and size of pores were increased with increasing vibration intensity in unmodified LM25 and LM6 alloys. The modification with metallic sodium in LM25 and LM6 alloys produced fewer but larger pores than found in unmodified alloys in the static condition. Vibration at frequencies of 31.7-41.7 Hz and amplitudes of 0.375-0.5 mm produced large holes on the top of the ingot in unmodified and modified LM25 and LM6 alloys. The effect of vibration levels on microstructure of the alloy at different pouring temperatures is shown in the Fig. 5.

![Figure 5: Effect of Vibration Acceleration Level on Microstructure of Al-Si-Mg Alloy [35]](image)

5. Effect of Heat Treatment

Cast Al 7Si-0.3Mg alloys can be heat treated to obtain an optimum combination of strength and ductility. The heat treatment consists of solutionizing at temperatures close to eutectic temperature, quenching and a combination of natural and artificial aging. The enhancement in tensile properties after the thermal treatment has largely been attributed to the formation of non-equilibrium precipitates of Mg2Si within the primary dendrites during aging and the changes occurring in Si particle characteristics from the solution treatment. Al-7Si-0.3Mg is a precipitation hardening alloy. The common heat treatment
A Review on the Effects of Casting Quality, Microstructure and Mechanical Properties of
Cast Al-Si-0.3Mg (LM25) Alloy

procedure applied is solution treatment followed by quenching in warm water and then precipitation or age hardening (T6 condition). The prescribed solution treatment schedule is at 798-818 K for 12 hours and age hardening at 428-448 K for 8-12 hours.

Man Zhu et al. [36] have studied the effect of T6 heat treatment on microstructure, tensile properties and fracture behavior of modified A356 Alloy with Misch metal containing La and Ce. Micro-structural analysis showed that the size of eutectic silicon particles was greatly reduced and the extent of spheroidization of Si particles was remarkably improved for the modified A356 alloys. Comparison between the unmodified and modified alloys suggested that the values of mean diameter, roundness, and aspect ratio of eutectic silicon particles were decreased within the Si primary dendrites during aging and the changes occurring in Si particle characteristics from the solution treatment. Al-7Si-0.3Mg is a precipitation hardening alloy. The common heat treatment procedure applied is solution treatment followed by quenching in warm water and then precipitation or age hardening (T6 condition). The prescribed solution treatment schedule is at 798-818 K for 12 hours and age hardening at 428-448 K for 8-12 hours.

6. Conclusions

In this article, the effects of heat treatment on the microstructure, quality of casting and mechanical properties of Al 7Si-0.3 Mg alloy were investigated. The following conclusions may be drawn based on the assessment of investigations on LM25 alloy:

1. Chemical modification with melt treatment, mould vibration during solidification and T6 heat treatment are found to be successful in modifying the morphology of eutectic silicon and refine the size of primary aluminium.
2. T6 Heat treatment with a solutionizing temperature of 530-540°C, solutionizing time of 8-10 hours and Aging period of about 6-12 hours is found to be optimum for Al-7Si alloys. The excessive additions of Na, Sr has led to over modification and coarsening of Si; the use of Sb is not recommended as it is a toxic substance and reacts with hydrogen to produce toxic stabine gas.
3. Trace additions of Na, Sr, Ca and Sb and Minor additions of rare-earth elements such as Lanthanum (La), Cerium (Ce), Yttrium (Y) and Misch Metal (MM) are found to be effective in modification of Al-Si alloys.
4. Al-Ti-B group of master alloys could be effective nucleants for Al-Si hypo eutectic and eutectic alloys and mould vibration in the low frequency range is found to be effective in refining the grain size of primary Aluminium and reduction of porosity.
5. As solidification rate is another important dependent factor on microstructure and experimental methods are expensive to assess the solidification, mathematical modeling and numerical analysis are increases the quality of casting and mechanical properties.

LM25 Alloy based metal matrix composites is another important area which has future scope for research due to their wide-ranging applications. Further scope of research may be viable for the effects of heat treatment on the mechanical properties of Al-7Si-0.3Mg alloy based on the above findings.
Acknowledgement

The author is grateful to Er. A. C. S. Arun Kumar, The President, Dr. M. G. R. Educational and Research Institute University, Chennai-600 095, India for his support and provide the research facility to complete this work successfully.

References


A Review on the Effects of Casting Quality, Microstructure and Mechanical Properties of Cast Al-Si-0.3Mg (LM25) Alloy


S. Nallusamy is currently working as Professor and Dean in the Department of Mechanical Engineering at Dr. M. G. R. Educational and Research Institute University, Chennai, India. He received his B.E. in Mechanical Engineering from Madras University and M.E. in Industrial Engineering from Anna University. Also he has been awarded his Ph.D in the area of Reliability Engineering for Transport Vehicles from Jadavpur University, Kolkata in the year 2009. His research interests include Surface Coatings, Composite Material, Characterization Techniques of Nanocomposites, TQM, Supply Chain Management etc. He has published thirty two papers in international and national journals and eighteen papers in conferences. Also he has published two text books of Industrial Engineering and Management and Automobile Technology. He has twenty three years of teaching and research experience.