70(10A): 311-317; 2022. DOI: 10.18311/jmmf/2022/32772

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: www.informaticsjournals.com/index.php/jmmf

Microstructure and Tribological Property Correlations of Die Cast and Spray Formed Al-30 wt.% Si Alloy

Chandra Mohan H. K[1], Devaraj S[2*], Narayana Swamy K. S[2] and Venkatesh B K[2]

[1]SJC Institute of Technology, Chickballapur 562 101, Karnataka, India. [*]Email: devaraj.s@reva.edu.in
[2]REVA University, Bengaluru 560 064, Karnataka, India

Abstract

Al-30 wt.% Si hypereutectic alloy was produced by die casting and spray forming technique. The microstructures, mechanical and tribological properties of the alloy were studied. The density of die cast and spray formed samples are measured using water displacement method by applying the Archimedes principle. The scanning electron micrographs of die cast and spray formed alloys revealed the morphological changes of silicon phase from coarse silicon needles to fine silicon needles due to high undercooling encountered in spray forming. The size of the hard silicon platelets are decreased from 22 µm to less than 10 µm as the processing method is changed from die casing to spray forming. The average Vickers micro hardness of die cast and spray formed alloy are 70.06±2.65 HV and 78.05±2.01 HV respectively. The respective yield strengths of die cast and spray formed alloy are 130±9MPa and 150 ±7 MPa and the compression strengths are 251±11.6 MPa and 283±6.32 MPa. The precipitation strengthening mechanism is found to be involved in spray formed alloy.

Keywords: *Alloys, Mechanical properties, Microstructure, Wear properties.*

1.0 Introduction

Al-Si alloys are widely used in aerospace and automobile industries, for making piston rings, engine blocks and cylindrical heads due to their high strength to weight ratio, low thermal co-efficient of expansion, excellent wear resistance, better mechanical properties and high corrosion resistance [1]. The contribution of different size and shape of Si phase in Al-Si alloys is significantly important factor for enhancement of properties. The conventional casting route of Al-Si alloy leads to coarse Si phase results in inferior properties of the alloy. The modification of Si phase in aluminum silicon alloy is possible because of addition of rare earth elements along with sodium. The maximum solid solubility of silicon in Al is limited to 1.65 wt.% at 577°C [2]. The presence of silicon in aluminum silicon alloy is an advantage to increase the fluidity of the melt during the casting process [3]. The silicon phase is extremely hard and is dispersed in the soft aluminum phase to enhance the mechanical as well as tribological properties [4]. Therefore, increasing the Si content in hypereutectic aluminium silicon alloy is of technological importance for significant improvement in properties. However, the increase in Si content in hypereutectic alloy enhances the formation of needle like silicon structure along with the large cuboids in primary silicon. This results in problems on castability, machinability and also adverse effect on mechanical and tribological properties [5]. The problems and adverse effect of Si phase on tribological and mechanical properties is of research interest for research scholars. The eutectic silicon

[*]*Corresponding Author*

content in an alloy is modified by adding sodium, strontium and phosphorus in the form of modifiers to refine the silicon morphology to improve the properties [6]. The silicon phase is also modified by changing the processing methods such as spray atomization and powder metallurgy route [7, 8]. Spray forming technique is a rapid solidification process and is employed to produce near neat shaped products. The spray forming technique involves the melting and atomization of the melt into fine droplets using inert gas and the droplets are made to consolidate on Cu substrate to form a deposit. The mass of the droplets in the spray are not deposited uniformly on the substrate from centre to periphery and it follows the bell shaped curve [9,10].

The microstructural investigations and tribological behaviour of spray formed aluminum silicon alloys produced for different processing parameters were investigated. Al-Si hypereutectic alloy are subjected sliding wear in automobile piston and cylinder engine parts. Therefore, it is of technical importance to study the tribological properties of the alloy.

2.0 Experimental Procedures

2.1 Die-casting and Spray Forming of Al-30 wt.% Si Hypereutectic Alloy

Al-30 wt. % Si alloy was melted in a graphite crucible using electrical resistance furnace. The temperature of molten metal and the furnace were monitored by R-type of thermocouple. An alloy of Al-30 wt.% Si (2 kgs) was produced by die casting and spray atomization process. The size of the rectangular metallic die used for die casting is 100 mm × 80 mm × 10 mm (l×b×t). After melting, one kg of melt was poured into a metallic die for die casting and remaining one kg of super heated melt was spray atomized to produce the atomized deposit.

The hypereutectic Al-Si alloy was spray deposited using the annular divergent nozzle to obtain the spray formed deposit. In order to maintain the proper fluidity of the melt, alloy was superheated to 100^{o}C before atomization. The thickness of spray formed deposit is not uniform throughout deposit. The thickness of the spray deposit is more at the centre than the peripheral region. In order to maintain the uniform thickness, the top surface, bottom surface and peripheral regions of the spray deposit was machined to form a rectangular deposit used for research work.

2.2. Density Measurements and Microstructure Analysis

The densities of die cast and spray formed samples were measured by Archimedes principle using Contech density tester. The weight of die cast and spray formed samples were measured in both air and water are measured to calculate the densities. The average density of die cast and spray formed samples are measured by considering the four samples from each alloy. The samples of die cast and spray formed alloys were polished separately using of different grades (1/0, 2/0, 3/0 and 4/0) of emery papers to eliminate the scratches. The emery paper polished samples are followed by alumina and diamond polishing. The samples were etched in Keller's etchant for the dwell time 25 seconds. The microstructure of the etched die cast and spray formed samples were investigated by Olympus optical metallurgical microscope (model BX53M). The distribution of the secondary phase and elemental analysis is carried out using TESCAN VEGA3 LMU scanning electron microscope.

2.3. Vickers Micro Hardness and Compression Test

The Vickers micro hardness of die cast and spray formed hypereutectic Al-Si alloy was measured by micro indentation test using Wilson VH1102 Vickers hardness tester. The hardness test was carried on polished die cast and spray formed samples with a applied load of 10N for dwell period of 10s. The compression test of die cast and spray formed samples was done using UT-01-0025 BISS 25kN computerized universal testing machine with a strain rate of 0.016 s^{-1}.

2.4. Wear Test

The wear behaviour and friction coefficient of die cast and spray formed alloy was measured using DUCOM TR20LE pin on disk wear testing machine. The samples size 50 mm × 10 mm × 10 mm (l×b×t) were taken from die cast and spray formed alloy for wear test. The wear tests of the samples for different loads (20, 40 and 60 N) and sliding velocity (1.67, 2.51 and 3.35 m/s) were carried out at room temperature. The wear track diameter 80 mm and wear time 10 minute was employed to conduct the wear test. Figs.4(a) and 4(b) show the worn out samples of die-cast and spray formed hypereutectic alloy respectively.

3. Result and Discussion

3.1. Silicon Morphology

The representative optical micrographs of die cast and spray formed size distribution of hard silicon phase in Al-Si hypereutectic alloy is shown in Fig.1(a) and 1(b) respectively. The silicon phase appears to be uniformly distributed within the aluminum matrix in both the cases of die cast and spray formed deposits. However, in both the cases the size and

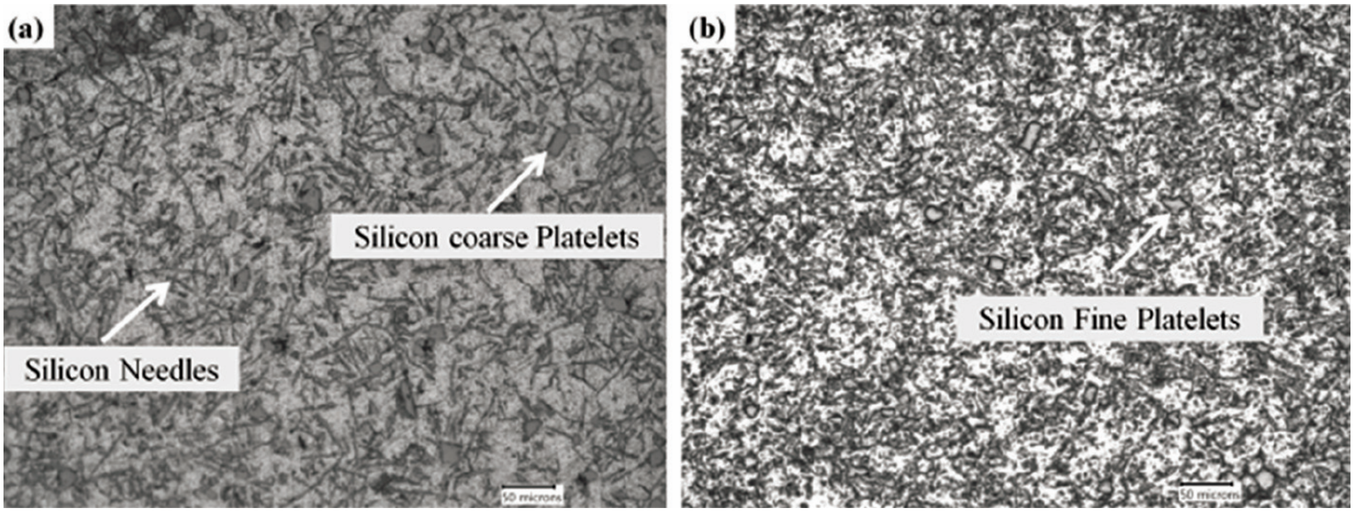

Figure 1: Optical micrographs of (a) die cast Al-30 wt.% Si hypereutectic alloy and (b) spray formed Al-30 wt.% Si hypereutectic alloy

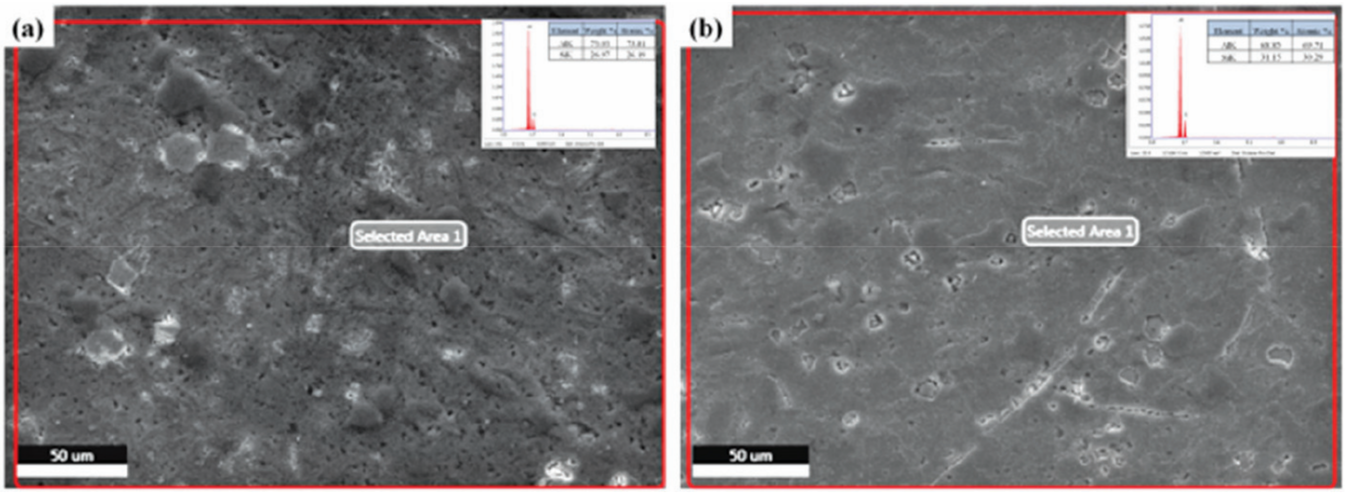

Figure 2: SEM micrographs with elemental analysis (a) die-cast Al-30 wt.% Si hypereutectic alloy and (b) spray formed Al-30 wt.% Si hypereutectic alloy

shape of the silicon phase in the matrix is different. The micrograph of die cast alloy shown in Fig.1(a) is the distribution of coarse particulate needle morphology of the silicon phase in a soft aluminum matrix. The coarse platelets and needle morphology of silicon phase is significantly changed to fine platelets of silicon morphology is depicted in Fig.1(b). The distribution of fine silicon platelets relatively increased further in spray formed deposit than the die cast alloy. The average size of the silicon particles decreased from 22 μm in die cast alloy to less than 10 μm size in spray formed alloy. The standard deviation of silicon particle size in cast alloy is 3 μm, whereas in spray formed deposit the standard deviation of size of silicon particle is less than 1 μm. The morphology (shape, size and distribution) of the silicon phase is significantly changed from needles and coarse platelets to fine equiaxed silicon particles when the processing method of aluminum silicon alloy is changed from die casting to spray formed route.

The elemental analysis of die cast and spray form alloy is evaluated by EDAX using SEM. The elemental analysis of die cast and spray form alloy are depicted in Figs.2(a) and 2(b) respectively. The EDAX report confirmed the presence and Al and Si in both the die cast and spray formed alloy.

The SEM images of die cast and spray formed alloy are shown in Figs.3(a) and 3(b) respectively. The distribution and morphology of silicon phase in both the cases are different. The die cast image shown in Fig.3(a) revealed the needle shaped silicon phase and their distribution, whereas spray

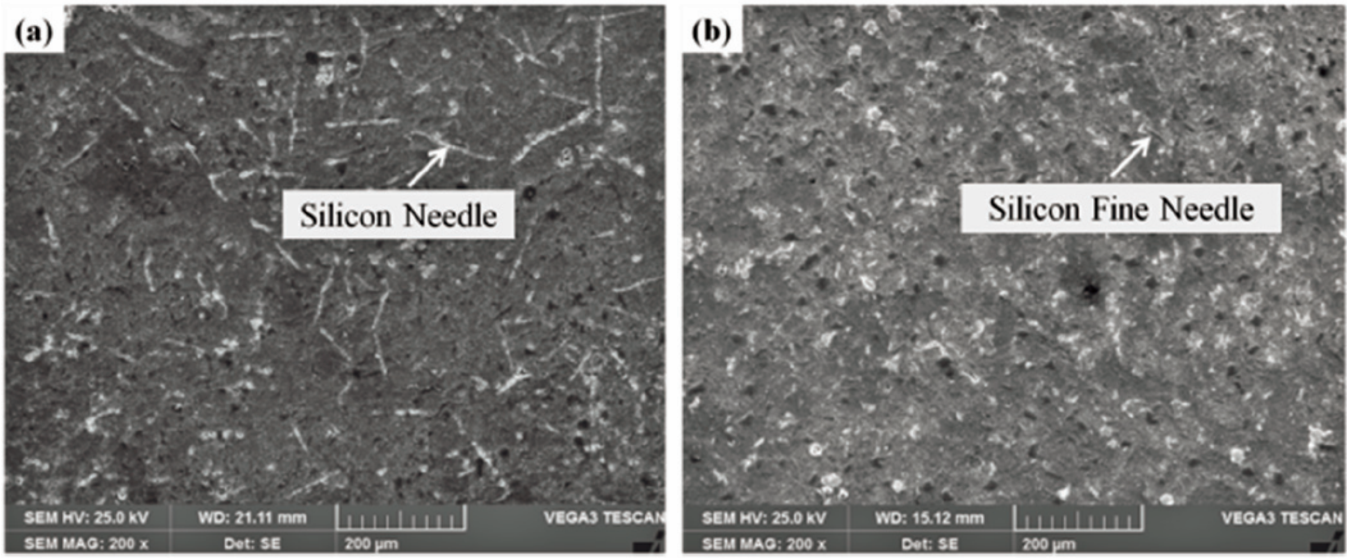

Figure 3: SEM morphology of distribution of silicon phase (a) die cast Al-30 wt.% Si hypereutectic alloy and (b) spray formed Al-30 wt.% Si hypereutectic alloy

formed image shown in Fig.3(b) revealed the distribution of fine silicon distribution. The course silicon needles are converted into fine silicon needle when the processing method is changed from die casting route to spray formed route. In the case of spray forming, the alloy is subjected to rapid solidification process during the atomization of the liquid.

3.2. Density

The average density of Al-Si alloy processed by die casting and spray forming technique shown in Fig. 8 are 2.494 ± 0.031 gm/cc and 2.678 ± 0.004 gm/cc respectively. The density of aluminum based Si alloy obtained by spray forming technique is decreased by 6.87% in contrast to die cast Al-Si alloy. The variations of density could be attributed to porosity present in the cast alloy compared to spray formed alloy. The marginal decrease in density in spray formed alloy is due to increase in porosity. In spray formed Al-Si hypereutectic alloy, the interstices formed between the solid particles are not filled with the liquid droplets due to lack of liquid fraction in the spray.

3.3. Vickers Micro Hardness and Compression Strength

The Vickers micro hardness of die cast and spray formed alloy is shown in Fig.4. The average Vickers micro hardness of die cast and spray formed alloy deposits are 70.06 ± 2.65 HV1 and 78.05 ± 2.01 HV1 respectively. The Vickers micro hardness value of spray formed alloy is 10.23 % higher than

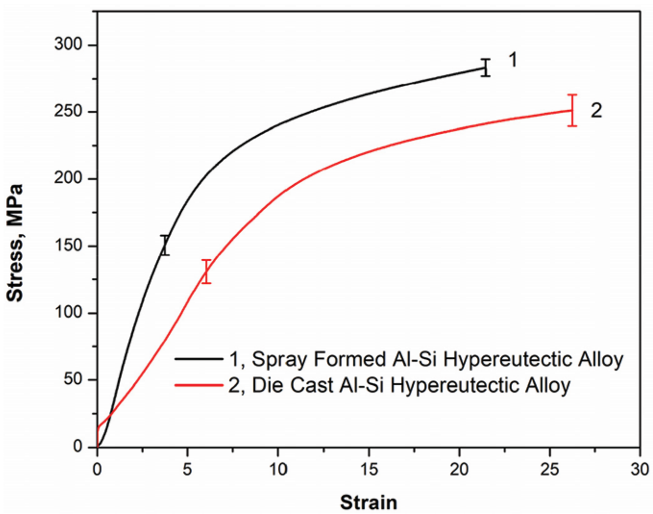

Figure 4: Compression stress–strain graph of die cast and spray form deposit Al-30 wt.% Si hypereutectic alloy

die cast alloy due to the uniform distribution of fine Si needles and platelets. The Si phase is very hard and uniform distributions of fine Si phase provide more resistance to indentation. The solubility of Si in aluminum is high in spray formed alloy than die cast Al-Si alloy. The solid solution strengthening mechanism could be other dominating mechanism in spray formed alloy than the die cast Al-Si alloy.

The stress-strain diagram of compression test die cast and spray formed Al-Si alloy is shown in Fig.10. The yield strength of die cast and spray deposit Al-Si alloy is observed

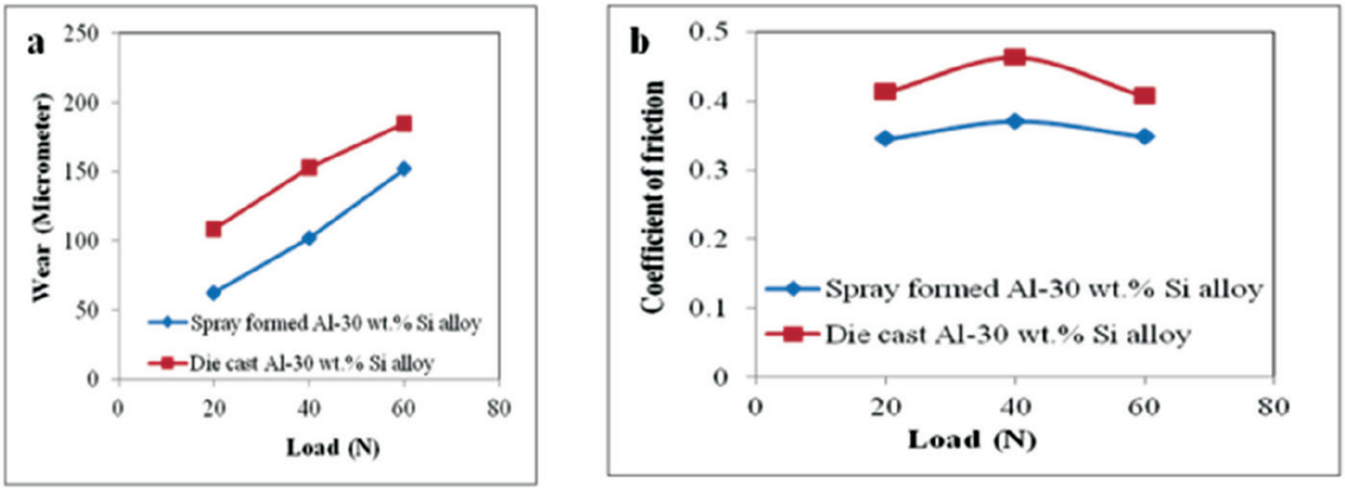

Figure 5: (a) Wear and (b) friction coefficient of die-cast and spray formed hypereutectic Al-30 wt.% Si alloy at constant sliding velocity of 2.51 m/s.

as 130 ± 9 MPa & 150 ± 7 MPa respectively and the respective ultimate compression strengths are 251 ± 11.6 MPa and 283 ± 6.32 MPa. The yield strength and ultimate compression strength of spray formed Al-Si alloy are increased by 13.3 % and 11.3 % respectively in contrast to die cast Al-Si alloy. The increase in yield strength and ultimate compression strength of spray formed alloy could be attributed to solid solution and grain refinement and precipitation strengthening mechanisms involved in spray formed deposit than die cast alloy. The solubility of Si in aluminum of spray formed deposit is another strengthening mechanism involved for increasing the strength of Al-Si alloy. The increase in solubility limit of silicon in spray forming process is possible because of increase in cooling rate during the spray forming process. The fine distribution of Si phase in the form of fine needles and platelets are dominating and found to be observed in spray formed Al-Si hypereutectic alloy.

3.4. Wear Performance and Coefficient of Friction

Dry wear test of Al-Si alloy produced by die cast and spray forming technique is conducted for various sliding velocity and loads. The wear performance of die cast and spray formed Al-Si hypereutectic alloys were conducted for different loads of 20, 40 and 60N with a constant sliding velocity of 2.51 m/s is shown in Fig.5a. The average wear performance of die cast and spray formed Al-Si alloys are reported as 148.67 ± 31.3 and 105.4 ± 36.7 respectively. The wear and tear is less in spray formed alloy than the wear and tear of the die cast Al-Si alloy. The fine size and shape of hard Si phase in spray formed alloy play a vital role for less loss of material than the coarse size distribution of hard Si phase in die cast Al-Si alloy.

The coefficient of friction as function of load of die cast and spray formed Al-Si alloy is shown in Fig.5b. The average coefficient of friction of die cast alloy for different loads at constant sliding velocity is 0.427 ± 0.025 and sprays formed alloy showed the friction coefficient of 0.354 ± 0.011. The coefficient of friction of die cast alloy is higher than the coefficient of friction of spray formed alloy. The size and shape of the Si phase present is the deciding factor for increasing the coefficient of friction in die cast alloy. The coarse Si phase is found to be distributed in die cast alloy in contrast to spray formed alloy.

3.5. Wear Track and Debris

Figs.6(a) and 6(b) show surface structure of worn surface and wear debris of die cast Al-30 wt.% Si alloy at sliding velocity of 2.51 m/s with 40 N constant load. The worn surface morphology of die cast Al-Si alloy depicts the large deep abrasive grooves formed by the ploughing action and delamination layers and is the evidence for involvement of abrasive wear mechanism. The formation of large deep abrasive grooves and delamination layers in the sliding direction of die cast Al-Si alloy increased the wear in contrast to spray formed alloy. Wear debris of die cast Al-Si 30 wt.% alloy shown in Fig.6(b) indicated the smaller particles and elongated flakes with various sizes. Figs.7(a) and 7(b) show the surface morphology of worn surface and debris of spray deposit Al-30 wt.% Si alloy at 500 rpm sliding speed under 40 N constant load.

Fig.7(a) shows the worn surface of spray formed hypereutectic Al-Si alloy and indicated the scratches and delamination layers. The wear debris of spray form deposit Al-Si 30 wt.% alloy as shown in Fig.7(b) indicated the presence of different size and shape of flakes. The ploughing

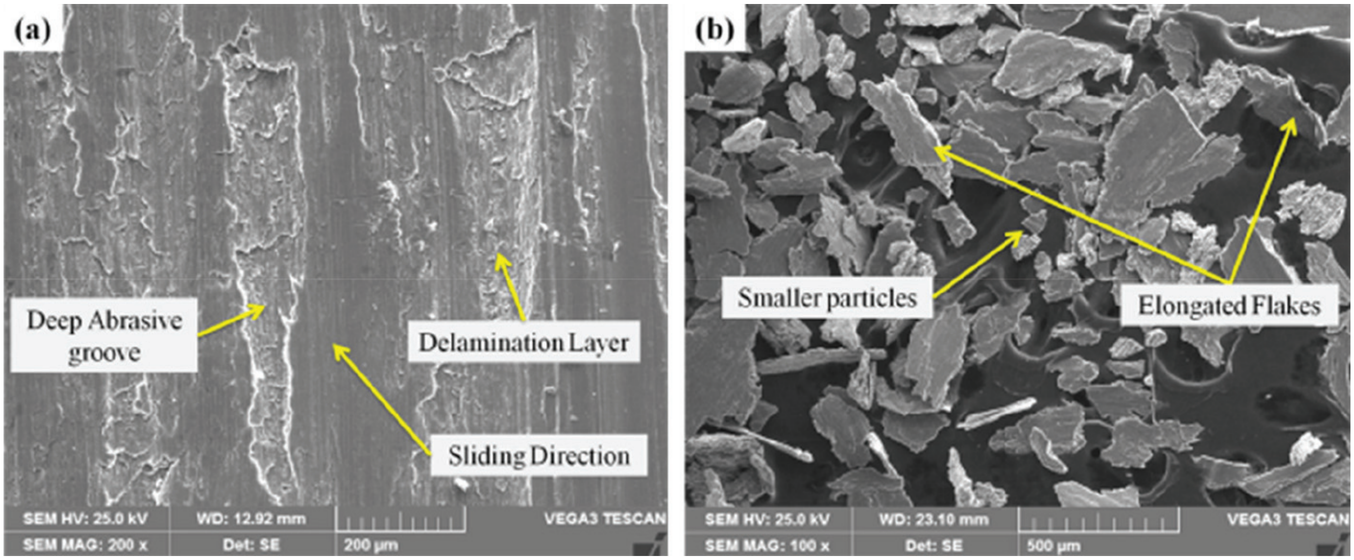

Figure 6: SEM micrographs of die-cast Al-30 wt.% Si hypereutectic alloy (a) worn surface and (b) wear debris

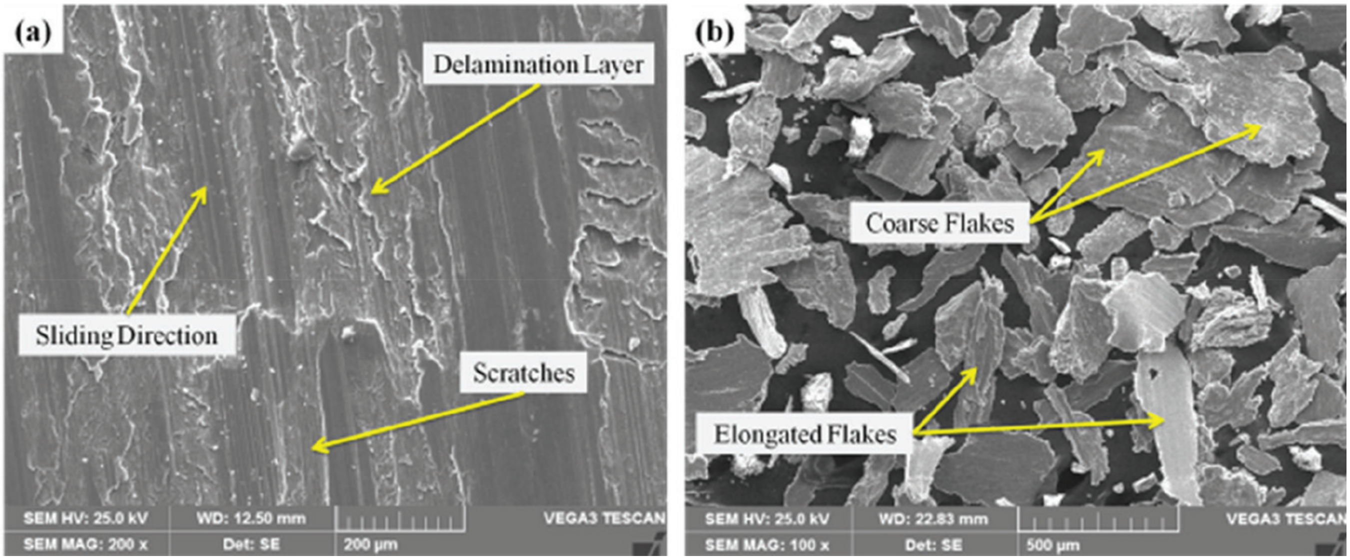

Figure 7: SEM micrographs of spray formed Al-30 wt.% Si hypereutectic alloy (a) worn surface and (b) wear debris

effect and delamination layer could be observed on the wear track in the sliding direction. In case of spray formed alloy, the majority of the debris is smaller in size and only few were bigger in size. This is because of metallurgical bonding of silicon particles are encountered in aluminum matrix.

4. Conclusions

The Al-30 wt.% Si alloys were die casted and spray deposited by die-cast and spray formed technique for comparative studies. The microstructures and surface topography of the silicon phase in both the alloys are different; this could be due to difference in solidification or difference in cooling rate of the alloy during processing of the alloys. The Vickers micro hardness, yield strength and ultimate compression strength of Al-Si spray formed alloy is higher than the die cast Al-Si hypereutectic alloy. This can be attributed to fine and uniform distribution silicon particles and the particles strengthening mechanism found to be observed in spray formed alloy. The wear and friction coefficient of Al-Si spray formed hypereutectic alloy is lower in contrast to Al-Si die cast hypereutectic alloy due to different size and distribution of silicon phase in aluminum matrix. The studies on wear track and debris indicated the involvement of mechanism of oxidation wear in both the die cast and spray formed alloys for all the sliding velocity and the loading conditions.

References

[1] Ojha KV, Aruna Tomar, Devendra Singh and Kaushal GC (2008): Shape, microstructure and wear of spray formed hypoeutectic Al–Si alloys. *Mater. Sci. and Eng*. 487: 591- 596.

[2] Wang R, Lu W and Hogan LM (1999): Growth morphology of primary silicon in cast Al–Si alloys and the mechanism of concentric growth. *J. Cryst. Grow.* 207: 43-54.

[3] Sabatino MD and Arnberg L (2009): Castability of aluminum alloy. *Trans. IIM* 62: 321-325.

[4] Zeren M (2005): Effect of copper and silicon content on mechanical properties in Al-Cu-Si-Mg alloys. *J. Mater. Pro. Tech*. 69: 292-298.

[5] Roy P, Sarangi SK, Ghosh A and Chattopadhyay AK (2009): Machinability study of pure aluminum and Al-12 % Si alloys against uncoated and coated carbide inserts. *Inter. J. Refra. Met. and Hard Mater*. 27: 535-544.

[6] Qiyang L, Qingchun L and Qifu L (1991): Modification of Al-Si alloy with sodium. Act. Metal. et Mat. 39: 2497-2502.

[7] Ojha SN, Jha JN and Singh SN (1991); Microstructural and modifications in Al-Si eutectic alloy processed by spray deposition. *Scri. Metal. et Mat.* 25: 443-447.

[8] Kim T, Lee B, Lee C R and Chun B (2001): Microstructure of rapidly solidified Al–20Si alloy powders. *Mater. Sci. Engg.,* A 304: 617-620.

[9] Srivastava VC, Mandal RK and Ojha SN (2001): Microstructure and mechanical properties of Al–Si alloys produced by spray forming process. *Mater. Sci. Eng.* A 304: 555-558.

[10] Fatahalla N, Hafiz M and Abdulkhalek M (1999): Effect of microstructure on the mechanical properties and fracture of commercial hypoeutectic Al-Si alloy modified with Na, Sb and Sr. *J. Mater. Sci.* 34: 3555-3564.