Wear Behavior Of Spray Formed Al–20 Mg_2Si Alloy

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Abstract

In the present study, Al–20Mg2Si alloy has been spray formed and subsequently hot pressed for porosity reduction. The micro structural features, microhardness and wear behavior of spray formed, hot pressed alloys have been evaluated and compared with as cast alloy. In spray deposition process the melt was gas atomized and deposited over a copper substrate. The microstructure of spray deposited alloy showed fine and uniformly distributed primary Mg_2Si *in the Al matrix. In contrast, a coarse polyhedral shaped morphology of the primary* Mg_2Si *phase was observed in the microstructure of the as-cast alloy. The microstructure was refined further after hot consolidation. The wear rate of spray deposited alloy was invariably lower than that of as-cast alloy. The improvement in wear properties of spray deposited alloy was discussed in the light of its micro structural modification, nature of worn surfaces and debris particles generated during wear.*

Key words*: hardness, hot pressing, microstructure, spray deposition process, wear.*

1. INTRODUCTION

Tremendous development has taken place in the production of non ferrous metals and their innumerable alloys and this “Materials Explosion” has now reached astonishing levels when compared with 19th century. As the technology improves, newer materials emerge from metals to alloys [1]. It is always a challenging assignment for a design engineer to have materials that have improved physical, mechanical and tribological properties. In addition, there is a critical need for light weight and high strength materials which are the most important aspects for various engineering applications (in the area of automotive, aerospace, deep ocean, nuclear energy generation and other structural applications) [2-3] . In this direction hypereutectic Al-Si alloy with high content of Mg offers the possibility of a significant decrease in density, increase in stiffness and high elastic modulus. Al-Si alloy containing high amount of Mg often results in formation of useful Mg_2Si intermetallic compound that exhibits high melting point, low density, high hardness, low thermal expansion coefficient, equilibrium interface and have a high potential for wear resistance applications [4-5].

Similarities exist between Mg_2Si and Si in terms of properties and solidification behavior [6].The most important advantage is the possibility of producing lighter components due to the lower density of Mg_2Si (1.99 g cm^{-3}) compared to Si (2.33 g $cm-^{3}$) which can contribute to the decrease in weight [7]. However, high content of Mg in hyper eutectic Al-Si alloy usually leads to the formation of coarse Mg_2Si phase under slow solidification condition and the wear properties of the as-cast alloys are not satisfactory due to the coarse Mg_2Si intermetallic [8].

It has been observed that a high amount of fine and uniform distribution of Mg_2Si phase in Al matrix, a considerable increase in wear resistance and a considerable decrease in density compared to Al-Si alloys. One approach that has been utilized to suppress the formation of the coarse primary Mg_2Si phase is rapid solidification (Spray deposition). Spray deposition process has an obvious modification in size, morphology and distribution of the primary Mg_2Si phase in matrix as well as reduction of segregation [9].

In this process, droplets are first atomized from a molten metal stream, quickly cooled by an inert gas, then deposited on a substrate, and finally built up to form a dense deposit with a required shape. However, in the as-sprayed condition, deposits always consist of some porosity, usually in the range 1 to 15 %. Therefore, the spray formed alloys requires further post-processing such as extrusion or hot compaction for the densification of deposit [10]. The densification and refinement of microstructure by thermo mechanical processing leads to substantial improvement in the mechanical properties of the spray deposited alloys. There are numerous studies in literature that refer to the production of Al alloys containing Mg_2Si particles [11]. However, the number of studies that investigate the wear behavior of Al-Mg_2Si alloy is limited. The objective of the present study is to investigate dry sliding wear behavior of spray-deposited Al–20(wt %) Mg_2Si alloy With observation and analyses of micro structural evolution, hardness, worn surface and wear debris of the alloy have been discussed.

2. Experimental procedure

The chemical composition of Al-20(wt %) Mg_2Si alloy is shown in Table 1. The details of spray forming set up employed in the present study, have been described else where [12]. In brief, spray forming process employed an annular convergent-divergent nozzle to create a spray of the melt. In each run 2.5 kg of alloy has been melted to a temperature of 800°C in a resistance heating furnace. The molten metal is atomized by a free fall atomizer using N_2 gas .The resultant spray is deposited over a Copper substrate resulting in a near net shape preform. The process parameters (variables) employed for producing the preform are listed in Table 2. Specimen of size 100 x 30 x 20 mm are cut from the preform and hot (temperature of 480°C) pressed at a pressure of 55 MPa for porosity reduction. Samples were extracted from as-cast and spray deposited and hot pressed alloy for microstructural examination. The samples were prepared by polishing using standard metallographic techniques of grinding on emery paper with 1/0, 2/0, 3/0 and 4/0 specifications. Final polishing was done on a wheel cloth using aluminium oxide powder The polished samples were etched with Keller's reagent (1% vol. HF, 1.5% vol. HCl, 2.5% vol. HNO3 and rest water).The microstructures of the samples were examined Scanning Electron Microscopy (Model: S-3400N Hitachi Model). Dry sliding wear tests were carried out on all the alloy specimens on a pin-on-disc wear testing machine (Model: TR-20, DUCOM). The counterpart disc was made of quenched and tempered EN-32 steel having a surface hardness of 65 HRC. Specimens of size Ø8×30 mm were machined out from all the alloys. The specimens were polished and then cleaned with acetone before conducting the test. The wear tests were conducted over a range of loads (9.81–68.67 N) and a sliding velocities (1.0, 1.5 and 2.0 m/s) at a constant sliding distance of 1000 m. The worn surfaces of wear specimen and wear debris after the test were examined under Scanning Electron Microscopy. The hardness measurement was carried out using Vickers Hardness Tester (Mattoon ATK-600) at an applied load of 300g.

Table 1: Chemical composition of Al-20 (wt%) Mg_2Si alloy

Material	Si	Mg	Fe	Ni	Zn	Mn	Cu	Ti	Cr
Al20 (wt%) Mg_2Si	7.63	12.72	0.17	0.01	0.01	0.01	0.01	0.01	0.01

Table 2: Process parameters

Process parameter	Value
Atomization pressure Mpa	0.7
Super heat temperature ° C	100
Gas-metal mass flow rate ratio	2.36
Deposition distance (mm)	380

3. Result and discussion

3.1 Microstructure

The SEM micrograph of as-cast of Al-20(wt%) Mg_2 Si alloy ,as shown in figure1, consists of a substantial amount of constituents. They form dendritic network structure. These constituents present in an irregular shape such as needles, plates and particles. The dendritic network structure of coarse primary irregular needle /plate-like β-Mg_2Si and presence of small amount of intermetallic Q-Al-Si-Mg phases were distributed non uniformly in the Al-matrix. The coarse and dendrite morphologies formed under low solidification rate resulting from eutectic reaction. EDS analysis results of the positions marked in those SEM micrograph of the different as cast constituents identified as Al-matrix, β - $Mg_{60}Si_{32}$ and Q-$Al_{30}Mg_{44}Si_{26}$ phases. Fig 2 shows the XRD pattern ofAl20Mg2Si alloy, it reveals that the components of the alloy consist of Al, Mg2Si and Si phases.

Fig.3 show the typical SEM microstructure of spray-deposited alloy , which is composed of fine intermetallic Mg_2Si phase with globular in shape and the small needle like intermetallic Q- Al-Mg-Si phase distributed uniformly in the Al-matrix. The presence of coarse, block/needle like primary Mg_2Si phase in the conventionally processed ingot metallurgy counterpart was suppressed. The average size of Mg_2Si particles is found to be 2–10 μm. The presence of particulate-like Mg_2Si dispersoids was attributed to the high cooling rate, associated with the rapid solidification processes .The EDS analysis and composition of phases exists in the alloy is as shown in the Table 3

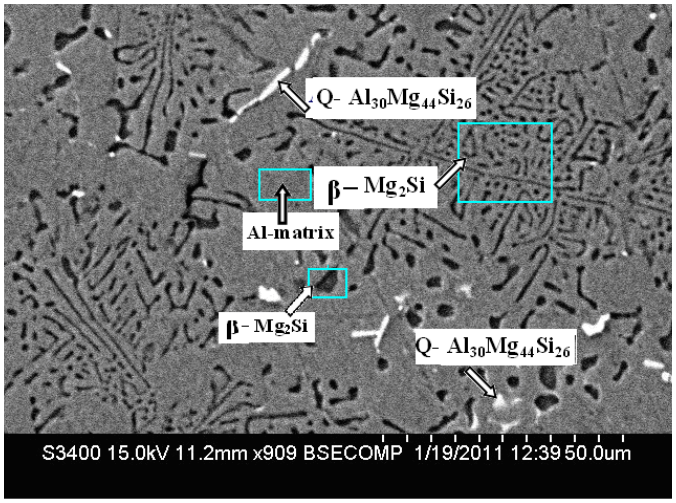

Fig 1: SEM micrograph of as cast Al-20Mg_2Si alloy

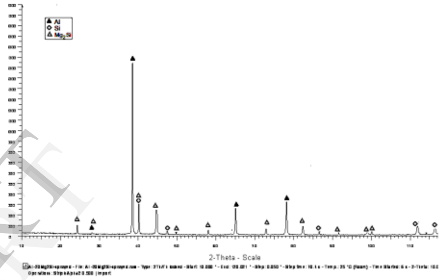

Fig 2 : XRD pattern of the Al-20Mg_2Si alloy

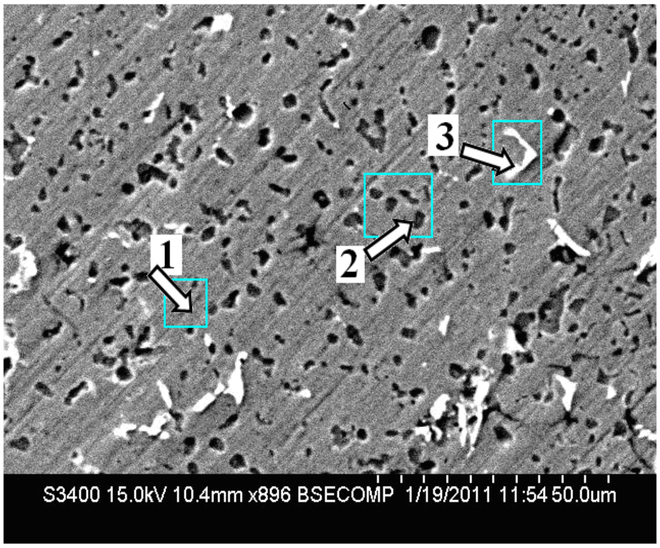

Fig 3 : SEM micrograph of spray deposited Al-20Mg_2Si alloy

Table 3: EDS analysis of spray deposited Al-20Mg2Si alloy

Location	Composition	Phase	*Al-K*	*Mg-K*	*Si-K*	Fe-K
Point 1	Al_{99}	α - Al matrix	96.07	0.93	0.30	0.83
Point 2	$Mg_{60}Si_{32}$	β -Mg_2Si	08.20	52.77.	32.78	0.00
Point 3	Al_{30} Mg_{44} Si_{26}	Q- phase	29.22	38.89	26.63	0.39

The microstructure of spray formed and hot pressed alloy is shown in Fig4 It clearly shows a refinement of Mg_2Si phase due to hot pressing and also some possible dissolution as the hot pressing was carried out at a high temperature of 480°C. It is obvious from the micrograph that the individual grain is more prominent and intermetallic phases are formed particularly at the grain boundaries. The partial recrystallization and fragmentation of secondary phase (Q) led to reduced porosity level. During hot pressing, the elements in the solution are precipitated at the boundaries

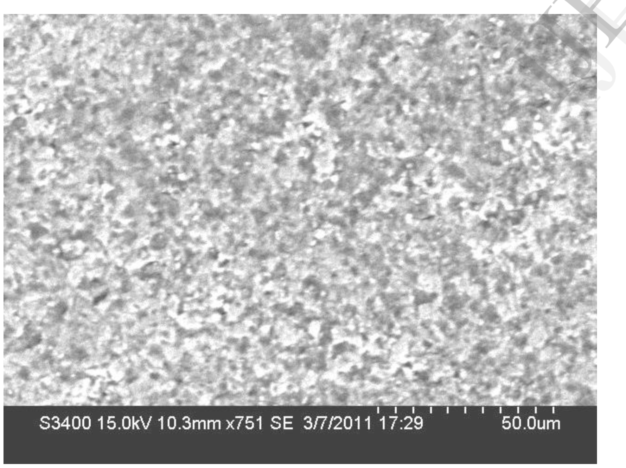

Fig 4 : SEM micrograph of spray deposited and hotpressed Al-20Mg_2Si alloy

3.2. Wear studies

The wear rate Al-20(wt%)Mg_2Si alloy for the range of loads and sliding velocity of 2m/s at a constant sliding distance of 1000 m are shown in Fig5. The load is varied from 9.81 -68.67N. It is observed from the Fig. 5 that the wear rate is increasing with increase in the load for all the alloys irrespective of alloy processing condition. In the entire range of applied loads, the spray deposited and hot pressed alloy showed lower rate than the as-cast and spray deposited alloy. The wear rate of spray deposited alloy showed little higher than that observed in spray formed + hot pressed alloys. The reason is due to the presence of pores in the former alloy.

Fig 6 shows the effect of sliding speeds (1.0, 1.5, and 2.0 m/s) on the wear rate of hot pressed spray deposited alloy for a range of loads between 9.81-68.67N. It can be seen from the figure that, the increase in wear rate with the sliding speed and at low load of 9.81 N, the wear rates are less and comparable. At sliding velocity of 2m/s, hot pressed spray deposited alloy showed high wear rate in the entire range of load.

Fig 7 shows that the coefficient of friction of as cast, spray deposited and hot pressed alloys at sliding speed of 2m/s. It can be seen from the figure that the coefficient of friction decreases initially with increase in further load , increased in load the coefficient of friction is more or less constant irrespective of processing condition but it is invariably low in hot pressed spray deposited alloy.

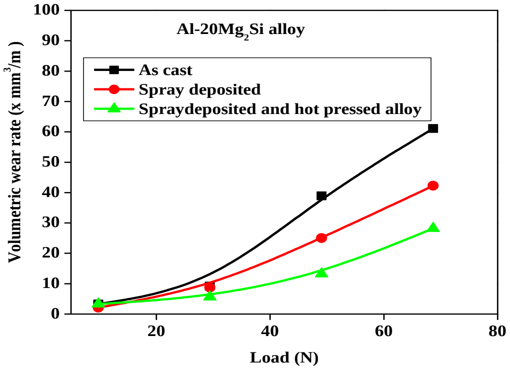

Fig 5: Variation of wear rate with applied load

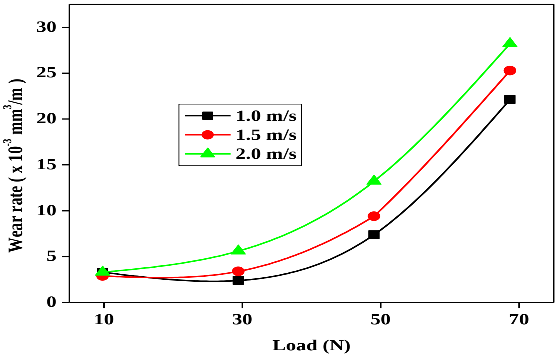

Fig 6: Variation of wear rate with sliding velocity

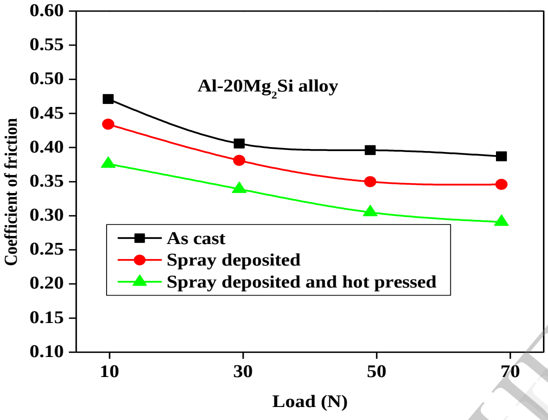

Fig 7: Coefficient of friction v/s applied load

3.3 .Worn surface and wear debris morphology

In order to investigate the wear mechanism, the surfaces of the worn samples were examined under SEM. Fig8 shows typical worn surface of the as cast alloy at the applied load of 68.67 N and sliding velocity of 2m/s. The worn surface clearly indicates the mark of an adhesive wear with plastic deformation The. gross plastic flow of metal, metallic fracture of ridges, edge cracking. It also reveals that some region exhibits delamination character. The block-like primary Mg_2Si particles are more easily detached from matrix and the debris of Mg_2Si particles is embedded in the matrix, resulting in deep and non-uniform grooves. Typical surface damage, abrasive scoring marks, deeper and wider craters are also clearly observable**.** Fig9 and Table4 shows that EDS result of wear surface of as- cast alloy and the composition of the alloy .It reveals that the surface exhibits small amount of oxygen besides Mg and Al, other elements such as Fe, Zn, Cu are not present(transfer from wear disc) as shown in Fig 9. It indicates that stable layer has been removed.

As seen in Fig.10 the worn surface of as-sprayed shows smooth appearance with small grooves due to plastic deformation on the surface and oxidation of asperities, indicating the existence of mixed metallic and abrasive wear. The low wear rate of the spray formed alloy compared to as-cast alloy is attributed to the micro structural refinement and large amount of fine and uniformly distributed Mg2Si particles in α-Al matrix. **.** Fig11 and Table5 shows that EDS result of wear surface of as-sprayed alloy and the composition of the EDS ,the result shows that the surface of as-sprayed alloy contain a certain amount of Fe , oxygen and Al, Mg, Si elements. It indicates that an oxidative wear and at high load, the primary Mg_2Si phases are fractured in the deformation layer. .

With increasing load, the fragmentation of Mg_2Si particles and their ability to support the load results in the direct contact of matrix with the counter face and a large strain within the α-Al matrix adjacent to contact surfaces. This might lead to the subsurface crack growth and delamination. The broken fine hard Mg2Si particles entrapped between the counter face and the alloy may act as third-body abraders that may be responsible for the homogeneous wear fine longitudinal grooves on the worn surface. The worn surface of spray formed + hot pressed alloy shown in Fig.12 reveals pronounced smooth sliding marks containing shallow grooves with smaller width ridges and few small dimples. The smaller width is due to the refinement of the primary M_2Si intermetallic caused during the hot pressing. For the material with higher hardness, abrasive wear tends to take place, while for material with lower hardness adhesive wear is encountered.

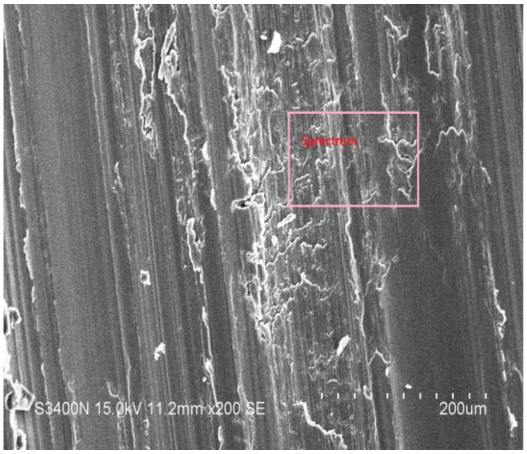

Fig 8: SEM morphology of worn surface of as-cast alloy at the load of 68.67 N

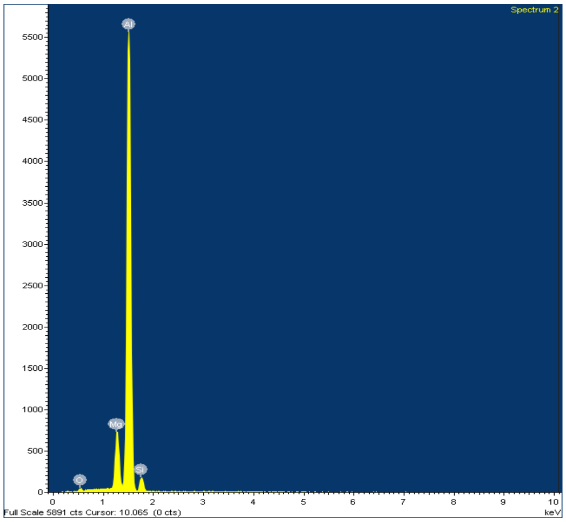

Fig 9: EDS result of wear surface of Al-$20Mg_2Si$ cast alloy

Table 4:

Element	Weight%	Atomic%
O K	1.98	3.28
Mg K	8.84	9.60
Al K	83.52	81.79
Si K	5.66	5.33
Totals	100.00	

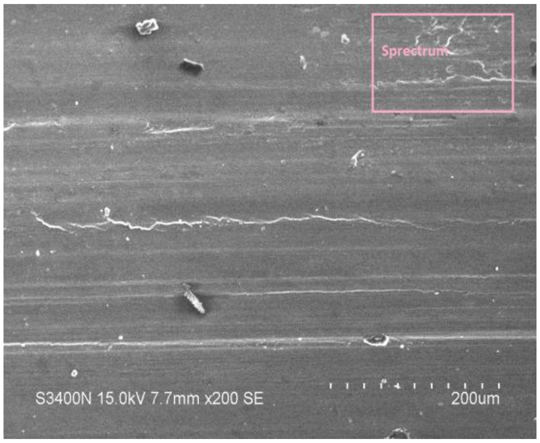

Fig .10: SEM morphology of worn surface of spray-deposited alloy at the load of 68.67 N:

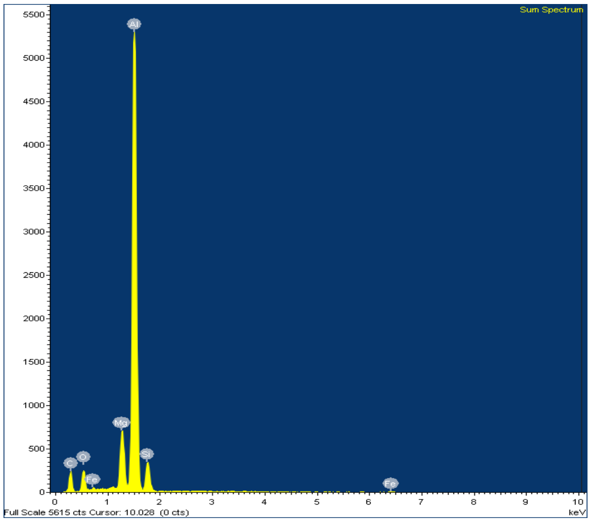

Fig 11: E DS result of wear surface of Al-$20Mg_2Si$ sprayed alloy

Table 5:

Element	Weight%	Atomic%
C K	25.76	41.62
O K	9.96	12.08
Mg K	6.29	5.02
Al K	51-84	37.28
Si K	5.40	3.737
Fe K	0.76	0.26
Totals	100	

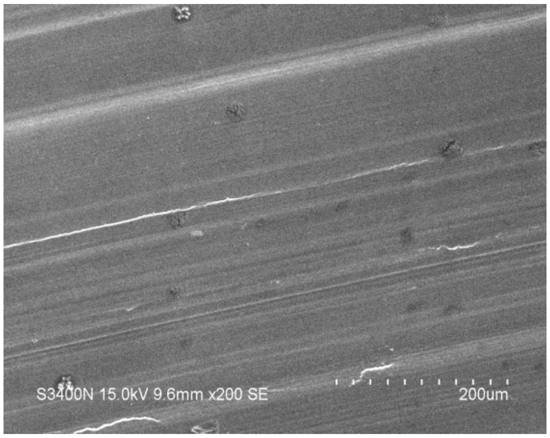

Fig 12:. SEM morphology of worn surface of spray- deposited and hot pressed alloy at the load of 68.67 N.

Various shapes and sizes of wear debris were found as a result of dry sliding test. The shape and sizes of wear debris varied from coarse flakes to fine particles. Changes in morphology of wear debris were found to be in consistence with the severity of the worn surface. Fig.13 shows SEM micrograph of wear debris of as cast alloy at a load of 68.67 N; The wear debris consists of microchips and delamination flakes and plates in the wear debris .The number of the platelets were compact and appeared during plastic deformation, and the surface of the platelet had some flow lines of plastic deformation.

The wear debris of spray-deposited alloy is composed of fine particles, the average size of the particle is less 10 µm, as shown in Fig14.The SEM micrograph of hot pressed spray deposited wear debris as shown in the Fig 15 .The fine particulate and flakes wear debris.

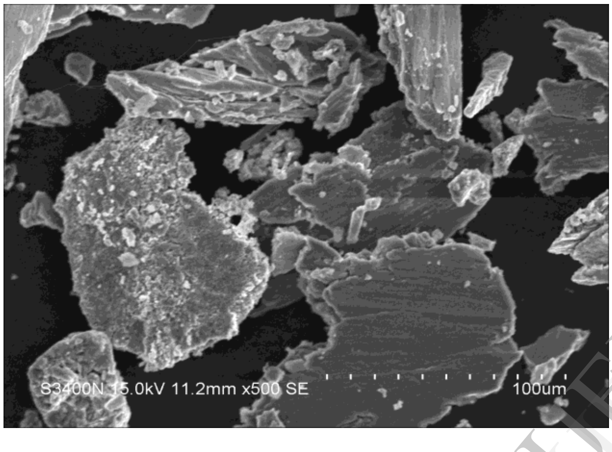

Fig.13 : SEM micrograph of wear debris of as cast alloy at load of68.67 N

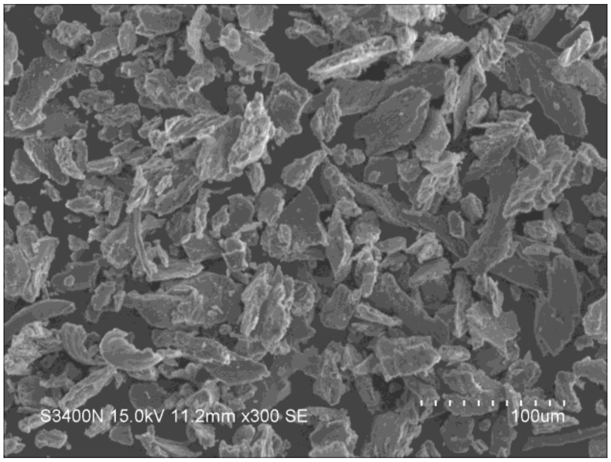

Fig.14 : SEM micrograph of wear debris of spray depositedalloy at load of68.67 N

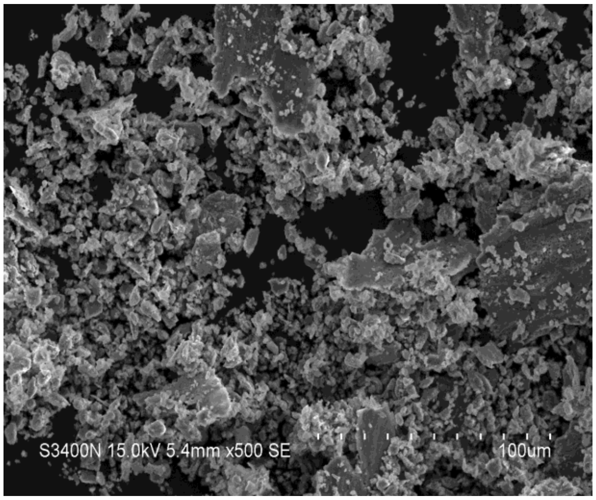

Fig.15: SEM micrograph of wear debris of spray deposited and hot pressed alloy at load of 68.67 N.

3.5 Hardness

The results of hardness measurement are shown in Table6. It is observed that the hardness of the spray formed alloys are higher than that of as-cast alloys.. The higher hardness of spray formed alloy can be attributed to the microstructural refinement in primary M_2Si phase owing to the rapid solidification effect A further increase in the hardness was observed in the spray formed and hot pressed alloy due to the partial recrystallization, fragmentation and redistribution of primary Mg2Si phase in α-Al matrix and reduced porosity. The microstructural changes from as-cast to spray formed and hot pressed alloys, could lower the stress concentration at the interface of the Mg_2Si particles and α-Al matrix. Therefore, the tendency to initiate the subsurface cracks is reduced resulting in a higher hardness

Table 6:

SNo	Sample	Vickers hardness (Load 300 gms)
1	Al-20(wt%)Mg$_2$Si cast	68
2	Al-20(wt%)Mg$_2$Si sprayed	82
3	Al-20(wt%)Mg$_2$Si sprayed and hot pressed	102

3.6 Discussion

Obviously the size of primary Mg$_2$Si intermetallic has a great influence on the wear rate of these alloys. During the wear tests, the coarse Mg$_2$Si phase fractured more frequently than the fine Mg$_2$Si phase. As the load increases, the shear stress in the alloy increases which in turn increases the amount of fracture in Mg$_2$Si phase and the deformation of the matrix in the surrounding area of Mg$_2$Si. The stress concentration resulting from such deformation may critically depend on the size of Mg$_2$Si particles and will be more severe at the interface between coarse Mg$_2$Si particles and the matrix compared to that between fine Mg$_2$Si particles and the matrix. This is observed in the present study that the coarse Mg$_2$Si phases fractured readily there by decreasing the wear resistance of the as-cast alloys. The good wear resistance of spray-deposited and hot pressed alloy can be attributed to the presence fine, uniformly distributed primary Mg$_2$Si in the Al- matrix. The refinement and further fragmentation of Q-intermetallics into fine particulates as well as reduced porosity due to hot pressing of spray deposited alloy. At low load of 9.81 N, the low wear rate of hot pressed spray-deposited alloy was due to the presence of high volume fraction of the primary Mg2Si phases that act as load-supporting elements. In order to remain as effective load-bearing elements, the particle-like Mg$_2$Si phases should maintain their structural integrity during wear. In this case, the local stresses generated beneath the slider are lower than the fracture strength of the Mg$_2$Si particles. The primary Mg2Si particles without fracture on the worn surface can scratch the counterpart surface and act as load supporting elements. The initial surface topographies of spray-deposited alloys are suitable to facilitate the transfer of the applied load onto the primary Mg2Si particles.

The primary Mg2Si particles stand proud of the polished contact surfaces; this is considered to be useful to prevent the softer Al matrix becoming directly involved in the wear process. During this process, the wear proceeds mainly by the formation of oxidation layer in the worn surface and its spalling. EDX was used to check the composition of worn surfaces of the pins, it showed that worn surfaces contain a certain amount of Fe and O, which indicates a typical oxidative wear .At low load wear is controlled by fracture of oxide layer and removal of oxide debris particles. With increasing load, the primary Mg2Si particles fracture above a certain load, and the fragmented Mg2Si particles lose their ability to support the load. In this case, the Al matrix comes in direct contact with the counterface. At high load of 68.67 N, concurrent with the primary Mg2Si particle fracture, high strain were generated within the Al matrix adjacent to contact surfaces. This led to the subsurface crack growth and delamination. The broken, hard Mg2Si particles entrapped between the counterface and the alloys may act as third-body abraders and be responsible for the production longitudinal grooves on the worn surfaces, as can be seen in Fig.10. It is also possible that the hard dispersoid particles or fractured pieces there are mechanically dislodged during wear. The delamination and third-body abrasion are identified as the two major mechanisms at high load of68.67 N.

The values of coefficient of friction for all alloys have a decreasing trend with increase in the normal load .This trend is attributed mainly to the oxidative regime operating before the plastic deformation and the fragmentation of Mg2si particles.

4. Conclusions

Spray forming is effective in refining the microstructures of Al-20Mg2Si alloys. The microstructures of as-spray formed alloys are further refined and the porosities have been considerably reduced by hot pressing. On the contrary the microstructures of as-cast alloys are coarser with long platelets of primary intermetallic Mg2Si and long needles of Q- Al –Mg -Si phases unevenly distributed in α-Al matrix. Increase in normal load increases the wear rate irrespective of alloy compositions and conditions.

With the increase of sliding velocity the surface temperatures of the material increases, which leads to the rise of plastic flow of surface and sub surface, and therefore wear rate increases. The wear surface of the casted material of Al–20(wt %) Mg2Si with 68.67N applied load during wear process shows high wear. There exist some broad grooves on surface of the Al–20(wt %) Mg$_2$Si Cast alloy. Mg$_2$Si reinforcement fractures and pulls out from the surface leaving the trace.

The high wear resistance and hardness for spray formed alloy was due to presence of fine and uniform distribution of brittle Mg2Si intermetallic. The refinement of microstructure by spray forming and densification by hot pressing improved the wear resistance and hardness of spray formed and hot pressed alloy. The coefficient of friction is low for spray formed and hot pressed alloy and high for as-cast alloy.

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