# Wear behavior of secondary processed spray formed Al-28Si-5Cu-4Mg alloy

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## Abstract

In the present study Al-28Si-5Cu-4Mg alloy has been spray formed and hot pressed for densification. Hot pressing refined the microstructure and reduced the porosity in the spray formed alloy from 10 to 1%. The microstructure of spray formed and hot pressed alloy exhibited equiaxed grain morphology with fine and uniform distribution of both primary and eutectic Si with fine needles of Q-$Al_{12}Si_7Mg_4Fe$ intermetallics and Chinese script like θ-$Al_2Cu$ precipitates in α-Al matrix. The size of Si particles ranged from 3–10 µm. In contrast the microstructure of as-cast alloy consisted of coarse primary and eutectic Si, long needles of Q-Al-Si-Mg-Cu-Fe phase and bright grey θ-$Al_2Cu$ phase in the α-Al matrix. The size of primary Si varied from 30–250 µm. The spray formed and hot pressed alloy exhibited a higher hardness compared to the as-cast alloy. The wear behavior of both the alloys, under dry sliding conditions, showed an increase in the wear rate with an increase in the load. However, the spray formed and hot pressed alloy exhibited maximum wear resistance and minimum coefficient of friction, while as-cast alloy exhibited minimum wear resistance and maximum coefficient of friction over the entire range of applied load. The high wear resistance and high hardness of spray formed and hot pressed alloy are explained in the light of its microstructural modifications induced during spray forming and subsequent hot pressing and also the topographical features of worn surfaces and morphology of debris particles.

**Key words:** Spray forming, Al-Si alloy, Wear, Hot pressing, Hardness.

## 1.0 Introduction

In recent years, hypereutectic Al-Si alloys have been studied extensively [Raj11, Raj12, Day13]. With increasing Si content, the stiffness and wear resistance increase but thermal expansion coefficient decreases. In order to enhance high temperature properties and thermal stability of the Al-Si alloys, alloying elements such as Cu, Mg, Fe and Ni are added. In conventional casting, addition of Cu and Mg to Al–Si alloys enables the formation of coarse intermetallic $Mg_2Si$, $Al_2Cu$ phases and other intermetallic compounds such as $Al_2CuMg$ and Al-Si-Cu-Mg. These coarse phases do not contribute to the strength and their degree of influence on ductility depends on their distribution and size relative to the Si particles [Wan03]. $Al_2Cu$ and Al-Si-Cu-Mg phases are relatively stable below 150°C and $Mg_2Si$ phase will coarsen over 180°C giving rise to a sharp decrease in high temperature strength [Wan09]. Additions of Cu and Mg also leads to the formation of bands of coarse Si particles and an increased risk for shrinkage porosity due to low solidification rate, which may decrease the elongation to fracture [Don05]. High strength and high wear resistance are imparted to the alloys when $Mg_2Si$, $Al_2Cu$ and Al-Mg-Si-Cu phases are present in the form of fine particulates, but results in a reduction of ductility. The coarseness of the microstructure including the fraction, size and distribution of intermetallic phases and the segregation profiles of solute in α-Al phase is dependent on the solidification rate. Formation of large and brittle intermetallic phases due to slow solidification may initiate fracture, decreasing elongation to fracture [Moh12]. In the past, few investigations have been carried out to modify these microstructures either by heat treatment or by addition of modifiers and refiners during casting process. However, very little success has been achieved by modification and refinement methods [Kim98]. This has led to the processing of such alloys through rapid solidification techniques like powder metallurgy and spray forming. Since powder metallurgy route involves a large number of processing steps in consolidation of powder particles, spray forming has been shown to provide a better opportunity for the synthesis of high-quality alloys [Lav96, Zho92]. So the objective of the present study is to make use of the combined effects of rapid solidification and the advantages of hypereutectic Al-Si alloy with Cu and Mg alloying elements. In this study, Al-28-5Cu-4Mg alloy was spray formed and hot pressed. The microstructural features of both as-spray formed and hot pressed alloys are reported. The effect of the modified microstructure of spray formed alloy on the wear behavior is studied and compared with that of as-cast alloy.

## 2.0 Experimental details

The chemical composition of Al-28Si-5Cu-4Mg alloy is shown in Table 1.

**Table 1**: Chemical composition of Al-28Si-5Cu-4Mg alloy

| Alloy | Si | Cu | Fe | Ni | Mg | Al |
|---|---|---|---|---|---|---|
| Al-28Si-5Cu-4Mg | 28 | 5.0 | 0.056 | 0.023 | 4.03 | Bal. |

The details of spray forming set up employed in the present study have been described elsewhere [Raj08]**.** In brief, spray forming process employed an annular convergent-divergent nozzle to create a spray of melt. In each run 2.5 kg of alloy has been melted to a temperature of 1018°C in a resistance heating furnace. The molten metal is atomized by nitrogen ($N_2$) gas. The resultant spray is deposited over a Cu substrate resulting in a near net shaped preform. The process variables employed in spray forming are listed in Table 2.

**Table 2**: Process variables in spray forming

| | |
|---|---|
| Melting temperature | 1018°C |
| Atomizing gas | $N_2$ |
| Gas pressure | 0.45 MPa |
| Nozzle to substrate distance | 0.40 m |
| Melt flow rate | 2.5 kg/min |
| Diameter of the delivery nozzle | 4 mm |

Specimens of size 100 x 30 x 20 mm were cut from the preforms. The specimens were hot pressed at a pressure of 55 MPa and a temperature of 480°C for densification. The density of spray formed alloys was measured by using Archimedes principle as per ASTM: B962 – 08.The percentage of porosity (% P) in the spray formed alloys was measured by using the actual density ($\rho_{ac}$) and the theoretical density ($\rho_{th}$) of the alloys using the relation, % P = [1 - ($\rho_{ac}$ / $\rho_{th}$)] x 100.

Samples were extracted from as-cast, as-spray formed and spray formed and hot pressed Al-28Si-5Cu-4Mg alloys 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 brasso and kerosene. The polished samples were etched with Keller's reagent (1% vol. hydrofluoric acid (HF), 1.5% vol. hydrochloric acid (HCl), 2.5% vol. nitric acid ($HNO_3$) and rest water). The microstructures of samples were examined under a ZEISS Optical Microscope and Scanning Electron Microscopy (Model: S-3400N Hitachi Model).

Wear tests were conducted on as-cast and spray formed and hot pressed alloy specimens on a pin-on-disc wear testing machine (Model: TR-20, DUCOM) as per ASTM: G99 – 05. The counterpart disc was made of quenched and tempered EN-32 steel having a surface hardness of 65HRC. Wear specimens of size Ø8×30 mm were machined out from both the alloys. The specimens were polished and then cleaned with acetone before conducting the test. The wear tests were conducted by varying the load from 10–70 N at a sliding velocity of 1.5 m/s and a sliding distance of 1025 m. The worn surfaces and the debris particles of both the alloys after wear testing were examined under Scanning Electron Microscopy. The hardness of the alloys was measured by Vickers Hardness Tester (Mattoon ATK-600) at an applied load of 300 g as per ASTM: E384 – 11e1.

## 3.0 Results and discussion

### 3.1 Microstructural features

Fig. 1(a) shows the optical microstructure of as-cast Al-28Mg-5Cu-4Mg alloy. The microstructure consists of coarse primary Si with eutectic network of Al-Si phase together with the intermetallic phases. Fig. 1(b) shows the optical microstructure of as-spray formed alloy, which is composed of uniformly distributed primary Si particles, intermetallic secondary phases containing Cu and Mg in Al-matrix. The microstructure shows a significant difference to its as-cast counterpart.

It is observed from the Fig.1 (b) that the primary Si particulates and fine needle shaped intermetallics are evenly distributed in Al-matrix. The presence of fine, spherical and approximately 10% of porosity has been observed in the as-spray formed alloy. Fig. 1(c) shows the optical micrograph of spray formed and hot pressed alloy. It can be observed from the figure that there is a fragmentation of Si and brittle θ and Q intermetallics in the Al-matrix and porosity has been reduced to 1%.

The SEM micrograph of as-cast alloy shown in Fig. 2 (a) is mainly composed of polygonal block like Si, dark grey colored needles of Q-$Al_{68}Si_{13}Mg_8Cu_6Fe_4$ phase and bright grey θ-$Al_2Cu$ phase in the form of Chinese script. The SEM micrograph of as-spray deposited alloy is shown in Fig. 2 (b). The microstructure of alloy exhibited coexisting faceted primary Si particles and fine plates of complex intermetallic phases. The size of Si particles varied from 3 to 10 µm compared to large particle size of 150 µm in as-cast alloy. The various phases present are grey colored Si particulates as a major element, grey colored intermetallic Q-$Al_{48}Si_{29}Mg_{18}Fe_4$ phase and bright white phase of θ- $Al_2Cu$.

The solidification of as-cast Al-28Si-5Cu-4Mg alloy, due to slow cooling rate and broad temperature interval between the liquidus and solidus of higher Si content in the pseudo binary section will cause castings with a coarse plate like Si, needle like Q and Chinese script like $Al_2Cu$ phases. In spray forming process, the solidification phenomena changes due to the effect of high cooling rate during the atomization stage and the unique microstructural evolution mechanism after deposition.

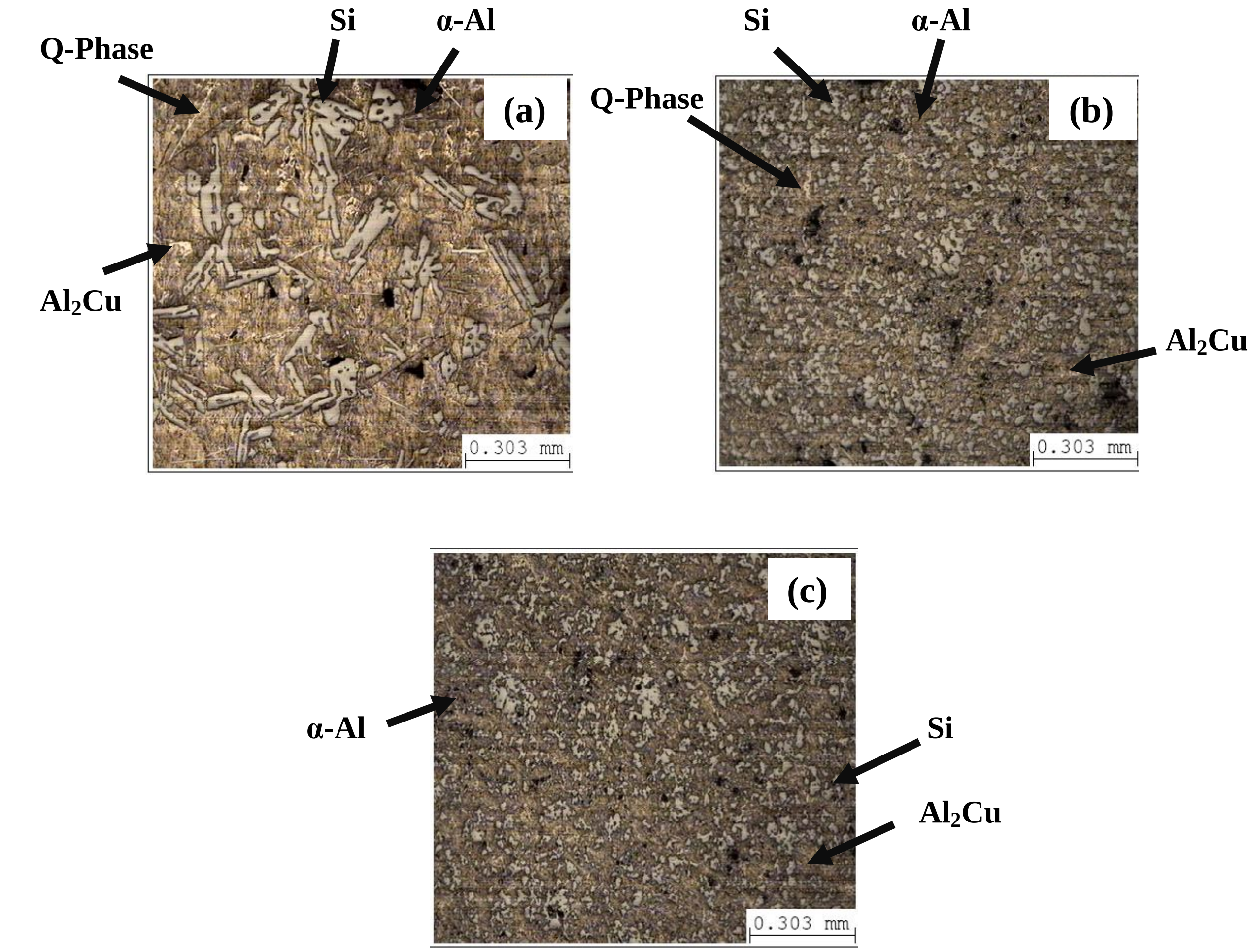


**Fig. 1**: Optical micrographs of Al-28Si-5Cu-4Mg (a) as-cast alloy (b) as-spray formed alloy (c) spray formed and hot pressed alloy

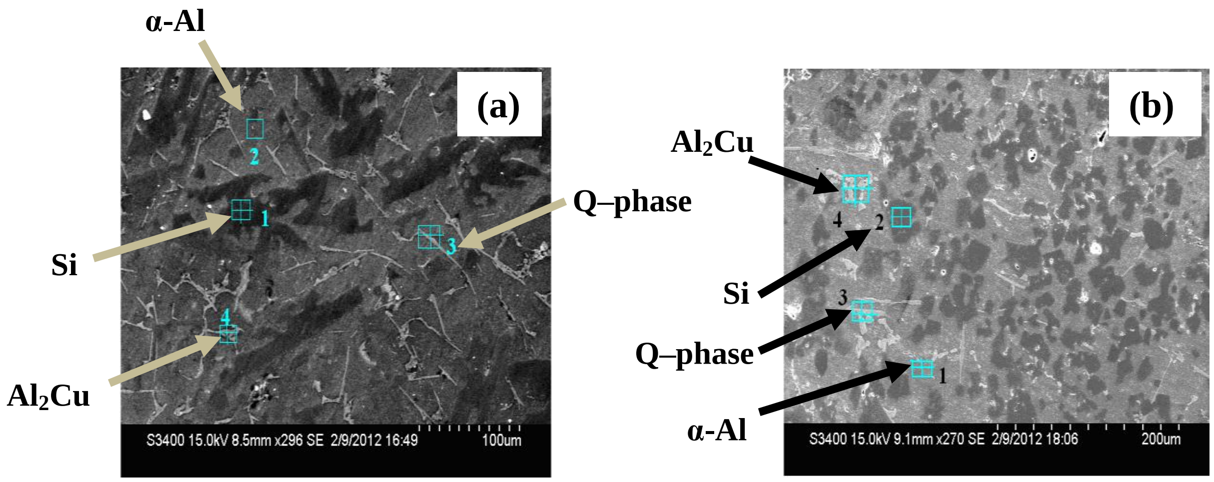


**Fig. 2**: SEM micrographs of Al-28Si-5Cu- 4Mg (a) as-cast alloy (b) as-spray formed alloy

As the cooling rate increases during atomization, the droplets experience a large under cooling prior to nucleation of primary Si phase leading to refinement. Simultaneously, reduced temperature suppresses the growth of these phases even after the deposition. Thus, large amount of fine and uniformly distributed Si and greater number of precipitates ($Al_2Cu$ phase, Q phase) are seen in the as-spray formed alloy. The dendritic as well as the Chinese script structures observed in the as-cast alloy are modified and it is difficult to discern the difference between primary $Al_2Cu$ and Q phases.

Hot pressing of as-spray formed alloy led to a considerable reduction in porosity, grain recovery and recrystallization to a certain extent. The preheat treatment before compression process makes the microstructure more uniform. Secondly, hot deformation leads to micro structural refinement and solid-state phase transformation. The severe stress imposed by hot compression generates high density dislocations in the grains. Subsequently, the movement and arrangement of dislocations form a lot of small angle grain-boundaries, refining initial grains into several substructures. In addition to the refinement of grains, hot deformation also promotes homogeneous precipitation hardening of θ phase and Q phase which can pin the movement of dislocations to restrain grains coarsening during recrystallization effectively [Est90].

### 3.2 Hardness

The results of hardness measurement show that the hardness of spray formed and hot pressed alloy is (142 VHN) higher than that observed in the as-cast alloy (82 VHN). The higher hardness of spray formed + hot pressed alloy can be atributed to the microstructrural refinement of θ-$Al_2Cu$ and Q phases owing to the rapid solidification effect and partial recrystallization, fragmentation of θ-$Al_2Cu$ and Q phases further and reduced porosity due to hot pressing. The hardness of the spray formed and hot pressed alloy is nearly 1.75 times higher than that of the as-cast alloy. The microstructural changes from as-cast to spray formed and hot pressed alloy could lower the stress concentration at the interface of Q phase and α-Al matrix. Therefore, the tendency to initiate subsurface cracks is reduced leading to an increased hardness in spray formed and hot pressed alloy [Sha07, Hua09].

### 3.3 Wear properties

Fig. 3 (a) shows the variation of wear rate with applied load and Fig. 3 (b) shows the variation of coefficient of friction with load for as-cast and spray formed and hot pressed Al–28Si–5Cu-4Mg alloys at a sliding speed of 1.5 m/s and a sliding distance of 1025 m respectively.

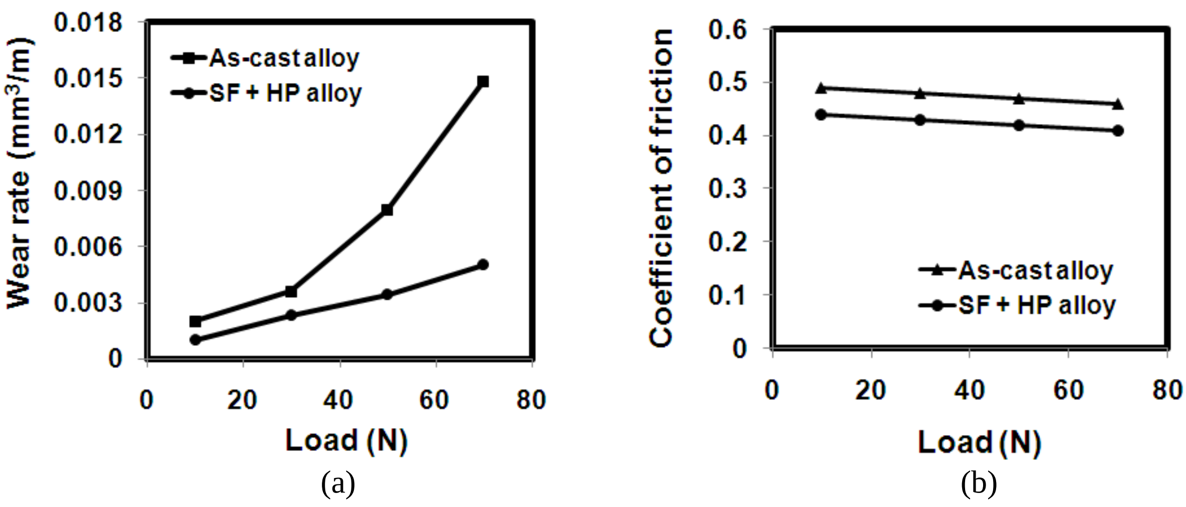


**Fig. 3**: (a) Wear characteristics and (b) friction plot of Al-28Si-5Cu-4Mg alloys

The wear rate increased as the load increased in both the alloys. It was observed that there is a remarkable difference in the wear rate, particularly at higher loads, in both the alloys. The wear rate of as-cast alloy is approximately 3 times higher than that of the spray formed and hot pressed alloy.

The microstructural features like morphology, size and distribution of hard intermetallics (Q-phase) and θ-$Al_2Cu$ precipitates have a large influence on the dry sliding wear behavior of alloy [Haq01]. The long needles of intermetallic Q-phase and coarse θ-$Al_2Cu$ phase appear to have played an important role in aggravating the wear process in as-cast alloy. The sharp edges of intermetallic Q-phase may have acted as crack nucleation sites resulting in a stress concentration that is more severe at the interface between the tip of needle-like intermetallic Q-phase and the Al-matrix [Wan04] that led to the fracture of long needles of Q-phase resulting in a high wear rate in as-cast alloy. The spray formed and hot pressed alloy showed lower wear rate compared to the as-cast alloy. The reduction in porosity, recrystallization and fragmentation of Q-phase and $Al_2Cu$ phase, their uniform distribution in the matrix of spray formed and hot pressed alloy, decrease the stress concentration between the fine needles of Q-phase and the matrix and increase the strength of matrix due to fine dispersion of $Al_2Cu$ resulting in an improved wear resistance.

At low loads, more time is available for the formation and growth of micro-welds, which increases the force needed to shear-off the micro-welds to keep the relative motion and this leads to an increase in wear resistance. An increase in the load results in the rise of the interface temperature that engenders oxidation and thermal softening of material. The brittle and discrete oxide film is harmful because it acts as a hard impurity or third body between mating surfaces [Ana09]. The wear rate with normal load shows a linear relation up to the load of 30 N. Further increase in the load to 70 N shows an abrupt increase in wear rate indicating a change in the wear mechanism. At high loads, the thermal softening of the alloy in the sub surface region takes place leading to a large scale plastic deformation [Moh96]. Under such conditions, metallic wear takes place. The remarkable observation in the present study is that the fine distribution of Q-phase and a good interfacial bonding at the interface with the matrix provided by the fine precipitates of θ-$Al_2Cu$, allows for high temperature stability leading to a low wear rate in spray formed and hot pressed alloy compared to that of as-cat alloy. It can be observed that coefficient of friction is lowest for the spray formed and hot pressed alloy and highest for as-cast alloy however; the variation of coefficient of friction with load is very small and can be assumed to be constant for both alloys over the entire range of load (Fig. 3 (b)).

### 3.4 Worn surfaces

The SEM micrographs of worn surface of Al-28Si-5Cu-4Mg alloys at a load of 70 N are shown in Fig. 4. The worn surface of as-cast alloy shown in Fig. 4 (a) consists of ploughing marks and a large number of pits indicating a high wear rate. The heavy damage may be due to the presence of long needles of Q-phase and coarse θ-$Al_2Cu$ phase and their uneven distribution in the alloy. It seems that the coarse phases are readily fractured and broken off during wear weakening the matrix leading to a high wear rate. In contrast the worn surface of spray formed and hot pressed alloy shown in Fig. 4 (b) consists of light scoring marks and shallow dimples in one or two regions clearly indicating a low wear rate. This may be due to the refinement in the microstructure where the Q-phase and θ-$Al_2Cu$ phase have been finely divided and uniformly distributed in the matrix. This fine dispersion provides strength to the matrix and the bonding between these phases and the matrix is strong enough to retain them to the matrix during wear leading to a low wear rate [Wan04].

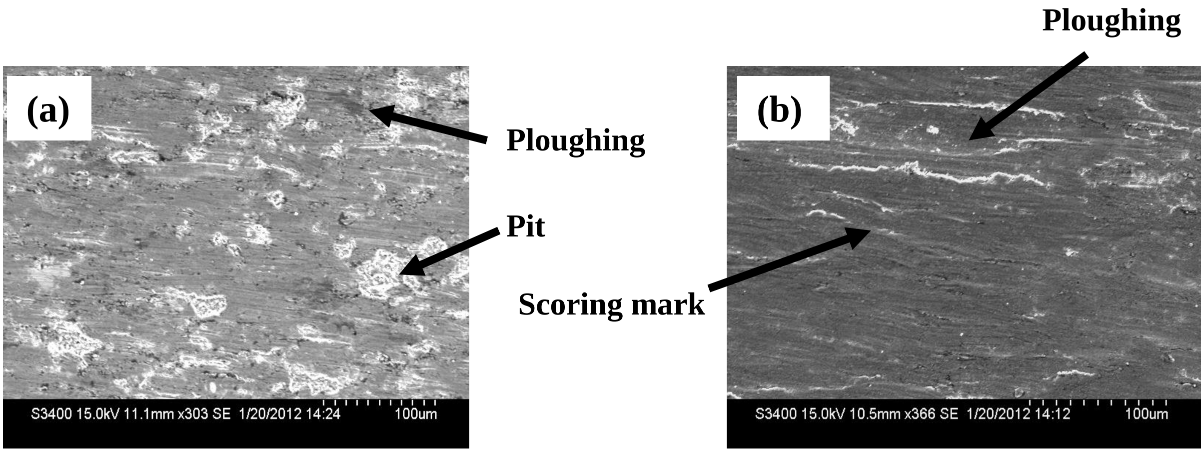


**Fig. 4**: Worn surface of (a) as-cast and (b) spray formed and hot pressed Al-28Si-5Cu-4Mg alloys at a sliding velocity of 1.5 m/s and a load of 70 N.

### 3.5 Wear debris

The SEM micrographs of wear debris of Al-28Si-5Cu-4Mg alloys are shown in Fig. 5. The wear debris of as-cast alloy is shown in Fig. 5 (a) and that of spray formed and hot pressed alloy is shown in Fig. 5 (b). Close observation of the micrographs reveals that the size of debris particles of as-cast alloy is bigger than that of spray formed and hot pressed alloy. The as-cast alloy consists of large flakes and bigger debris particles where as spray formed and hot pressed alloy consists of smaller flakes and fine debris particles. The size of wear debris particle was found to be related to the applied load and the hardness of the material [Ana10]. Since the hardness of spray formed and hot pressed alloy is higher than that of as-cast alloy, the size of its debris particles is smaller than that of as-cast alloy. The smaller size of the debris particles indicates that the wear rate of spray formed and hot pressed alloy is lower than that of as-cast alloy [Esh11].

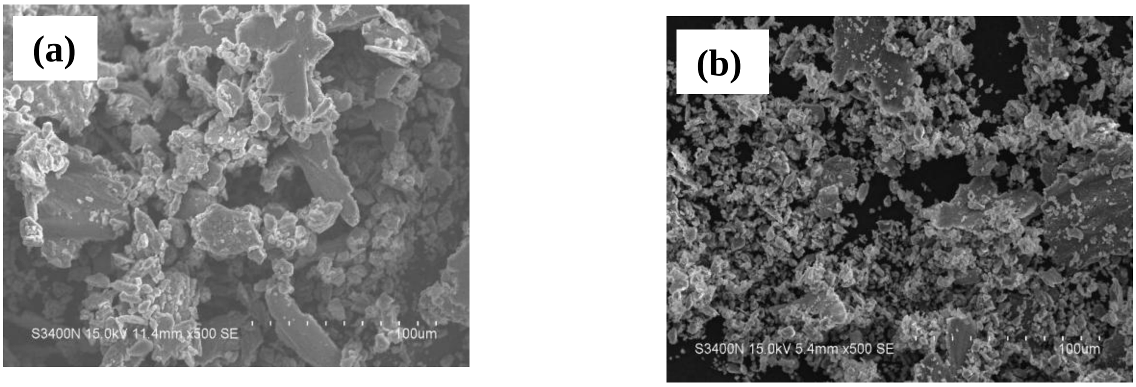


**Fig. 5**: Wear debris of (a) as-cast and (b) spray formed and hot pressed Al-28Si-5Cu-4Mg alloys at a load of 70 N and a sliding velocity of 1.5 m/s.

## 4. Conclusions

The following conclusions may be drawn from the present investigation on the spray forming and hot pressing of Al-28Si-5Cu-4Mg alloy.

(1) The microstructure of spray formed and hot pressed alloy consists of fine and uniform distribution of both primary and eutectic Si with fine needles of Q-$Al_{12}Si_7Mg_4Fe$ intermetallics and Chinese script like θ-$Al_2Cu$ precipitates in the Al-matrix.

(2) Hot pressing has reduced the porosity from 10 to 1 % in spray formed alloy.

(3) The hardness of spray formed and hot pressed alloy is 142 VHN and that of as-cast alloy is 82 VHN.
(4) The wear resistance of spray formed and hot pressed alloy is higher than that of the as-cast alloy. The worn surface is less damaged and the debris particles are smaller in spray formed and hot pressed alloy compared to that in the as-cast alloy.

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