Proceedings of the World Congress on Engineering 2013 Vol III,
WCE 2013, July 3 - 5, 2013, London, U.K.

# A Comparative Study on Microstructure and Tensile Properties of Spray Formed and Ascast Al-28Si-5Cu-4Fe and Al-28Si-5Cu-4Mg Alloys

G. B. Rudrakshi, D. M. Goudar, V. C. Srivastav

***Abstract*—In the present study, Al-28Si, Al-28Si-5Cu-4Fe and Al-28Si-5Cu-4Mg alloys were produced by spray forming and subsequently hot pressed for densification. The effect of alloy composition on the microstructure and mechanical behavior of spray-formed alloys were investigated. The microstructures consist of an equiaxed, nearly spheroidized grain morphology of $\alpha$-Al matrix. The spray formed alloys exhibited sharply decreased segregation and increased metastable solid solubility and greater volume fraction of Si particles and intermetallic phases. Spray formed Al-28Si-5Cu-4Fe alloy contains $Al_2Cu$, $Al_5FeSi$ along with Si. On the other hand, Al-28Si-5Cu-4Mg alloy showed $Al_2Cu$, $Al_{48}Si_{29}Mg_{18}$ and Si. Hot pressing lead to a significant reduction of porosity and partial recrystallization of spray formed alloys. The room temperature tensile tests of spray formed hot pressed alloys showed significant increase in ultimate tensile strength compared to as cast alloys. Spray formed hot pressed Al-28Si-5Cu-4Fe alloy exhibited superior ultimate tensile strength and significant increase in elongation to fracture. This may be attributed to the presence of homogeneous distribution of fine Si particles, high content of short needle-like $\beta$-$Al_5FeSi$ intermetallic and precipitation strengthening phases.**

***Index Terms*—Spray deposition, Hot pressing, Tensile strength.**

## I. INTRODUCTION

HYPEREUTECTIC Al-Si alloys have an excellent potential for applications in automotive and aerospace industries due to their high strength to weight ratio[1]. In order to improve the mechanical properties of hypereutectic Al-Si alloys, a modification in composition is necessarily made by adding alloying elements like Cu, Mg, Fe and Mn to these alloys [2]. Addition of Cu and Mg increases the strength of the alloy through formation of intermetallic phases such as $Al_2Cu$, $Mg_2Si$ and $Al_2CuMg$, however this also leads to a reduction in ductility. Addition of Fe enhances the strength at elevated temperature through the precipitation of intermetallic phases, such as $\delta$-$Al_4FeSi_2$, and $\beta$-$Al_5FeSi$ [3]. The formation of coarse plate-like silicon particles, needle-like intermetallic phases in conventional casting methods, results in inferior mechanical properties. On the other hand heat treatment or addition of modifiers and refiners during the casting process has little success. More recently, spray forming has received considerable attention as an alternative route for the synthesis of a variety of structural materials. In the spray forming process, droplets are first atomized from a molten metal stream, quickly cooled by an inert gas, deposited on a substrate, and finally built up to form a low-porosity deposit with a required shape[4]. The objective of the present study was to utilize combined effects of high cooling rate solidification and the advantages of hypereutectic Al-Si alloy alloyed with the other elements such as Cu, Fe and Mg. In the present investigation Al-28Si, Al-28Si-5Cu-4Fe and Al-28Si-5Cu-4Mg (wt %) alloys were spray deposited and hot pressed. The microstructural features of as cast, spray formed and spray formed hot pressed alloys are studied. The effects of the modified microstructure of spray deposited alloys on the mechanical properties are studied and compared with as cast alloys.

Manuscript received February 27, 2013; revised March 25, 2013.
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## II. EXPERIMENTAL DETAILS

The chemical composition of Al-28Si, Al-28Si-5Cu-4Fe and Al-28Si-5Cu-4Mg alloys is shown in Table I. The details of spray forming set up employed in the present study have been described elsewhere [5]. In each run 2.5 kg of alloy has been melted to a superheat temperature of $150^0$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 Cu substrate resulting in a bell shaped preform. The process variables employed for producing the preforms are listed in Table II. Samples were extracted from the central region of the deposits to prepare specimens of size 100 x 30 x 20 mm. The spray deposited specimens were hot pressed at a pressure of 55 MPa and a temperature of $480^0$C for porosity reduction. Samples were prepared from the as cast, spray formed and spray formed + hot pressed Al-28Si, Al-28Si-5Cu-4Fe and Al-28Si-5Cu-4Mg alloys respectively following a standard procedure for microstructural examination. The microstructures of the samples were examined under a ZEISS Optical Microscope and Scanning Electron Microscope (Hitachi S-3400N). Tensile samples of 16 mm gauge length and 4.5 mm gauge diameter were prepared from as cast and spray deposited hot pressed alloys. Tensile tests were conducted at room temperature on an INSTRON Universal Testing Machine at a cross speed of 0.05 cm/min and a chart speed of 2 cm/min. average values of three samples have been considered for tensile testing.

## III. RESULTS AND DISCUSSION

### *A. Microstructural features*

The microstructures of as cast alloys are shown in Fig. 1. Al-28Si alloy exhibited primary and eutectic Si phases in the

ISBN: 978-988-19252-9-9
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

TABLE I
CHEMICAL COMPOSITION (WT %) OF AL-28SI, AL-28SI-5CU-4FE AND AL-28SI-5CU-4MG ALLOYS

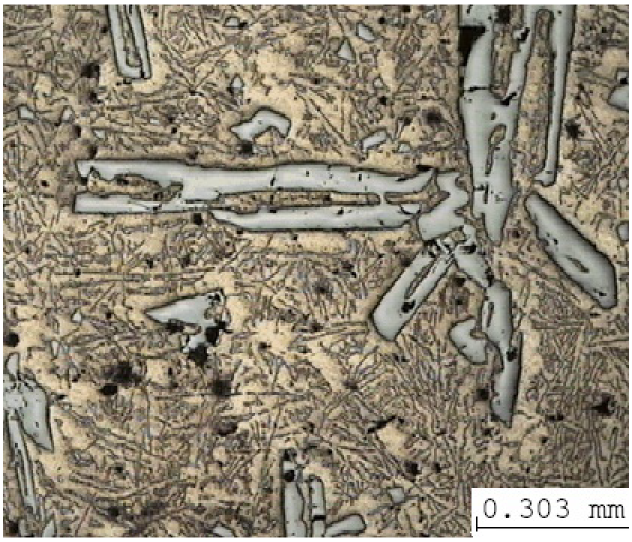
| Alloy | Si | Cu | Fe | Ni | Mg | Al |
|---|---|---|---|---|---|---|
| Al-28Si | 28 | 0.056 | 0. 05 | 0.035 | 0.123 | Bal |
| Al-28Si-5Cu-4Fe | 28 | 5.000 | 4.0 | 0.025 | 0.14 | Bal |
| Al-28Si-5Cu-4Mg | 28 | 5.000 | 0.056 | 0.023 | 4.03 | Bal |

TABLE II
PROCESS VARIABLES IN SPRAY FORMING

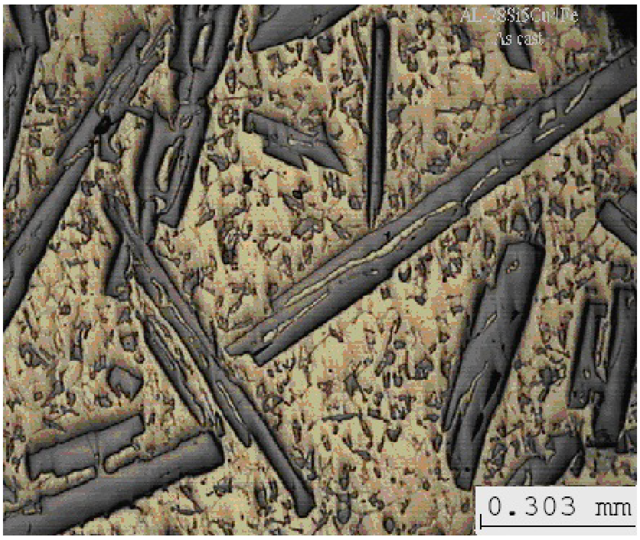
| | |
|---|---|
| Melt super heat temperature | $150^0$C |
| Atomizing gas | $N_2$ |
| Gas pressure | 4.5 (kg/cm$^2$) |
| Type of nozzle | Freefall |
| Nozzle to substrate distance | 390 mm |
| Melt flow rate | 2.48 (kg/min) |
| Diameter of delivery nozzle | 4 mm |

$\alpha$-Al matrix (Fig. 1(a)). The primary Si particles have plate like morphology with a size varying from 75-350 $\mu$m, while eutectic phase comprises of Si needles. As-cast Al-28Si-5Cu-4Fe alloy depicted a relatively coarse microstructure due to slow cooling rate associated with the process(Fig. 1(b)). The microstructure consists of block like Si particles, ternary $\beta$-$Al_4FeSi_2$ intermetallic sharp edged needles having a length ranging from 150-250 $\mu$m and $\theta$-$Al_2Cu$ phase. The $\beta$-phase is naturally a hard and brittle intermetallic with a needle form, which usually acts as a stress raiser and interferes with liquid flowing in the interdendritic channels during solidification [6]. Cu was found to exist mainly in the interdendritic $Al_2Cu$ phase seen around the $Al_4FeSi_2$ phase as Chinese script. Optical micrograph of Al-28Si-5Cu-4Mg alloy in the as-cast condition is shown in Fig. 1(c). The microstructure consists of polygonal block like primary Si, needle shape dark grey colored Q- Al-Mg-Si phase and bright grey $Al_2Cu$ phase in the form of Chinese script.

Fig. 2 shows SEM/EDS micrographs of spray formed alloys. The microstructures consist of an equiaxed, nearly spheroidized grain morphology of $\alpha$-Al matrix. The spray formed alloys exhibit sharply decreased segregation and increased metastable solid solubility and greater volume fraction of Si particles and intermetallic phases. The Si particles are very much refined and are uniformly dispersed in the Al-matrix. Si particles are in spherical shape having a mean size 12, 10 and 7 $\mu$m in the $\alpha$-Al matrix compared to large particle sizes in as cast alloys. A porosity of 12, 15 and 14 % with spherical morphology and nonconnected distribution was observed in the alloys respectively, which is an undesirable feature of spray formed alloys. The phase composition of the Al-28Si alloy is shown in Table III. Solid solubility of silicon in the eutectic phase (point 1,Fig. 2(a)) is enhanced compared to as cast alloy. Fig. 2(b). shows the microstructure of spray formed Al-28Si-5Cu-4Fe alloy. The EDS results of various phases present in the microstructure are shown in Table IV. The various phases are $\alpha$-Al (Point 1), $\theta$-$Al_2Cu$ (point 2), $\beta$-$Al_5FeSi$ (point 3) and primary Si (point 4). The bright phase could be identified as $\theta$-$Al_2Cu$ precipitates with globular morphology around very small needle shape intermetallics of $\beta$-$Al_5FeSi$. In addition, no banded microstructure was observed in this alloy. Fig. 2(c) shows the microstructure of spray formed Al-28Si-5Cu-4Mg




(a) Al-28Si alloy

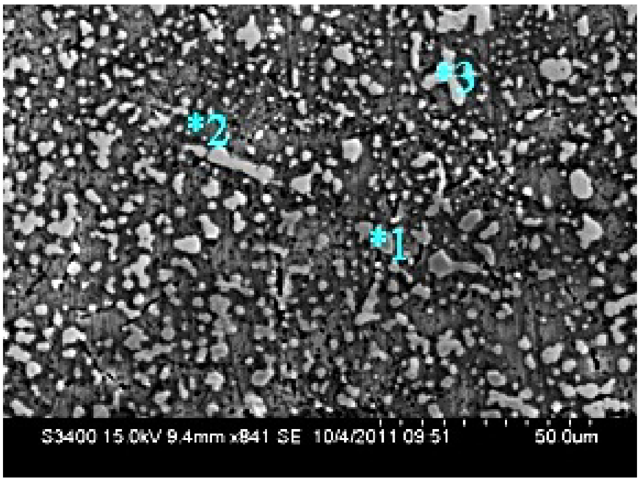



(b) Al-28Si-5Cu-4Fe alloy

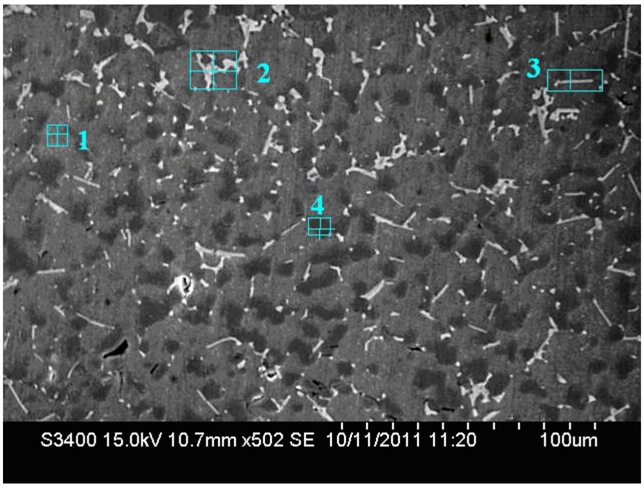

(c) Al-28Si-5Cu-4Mg alloy

Fig. 1. Optical Micrographs of as-cast alloys showing large Si particles.

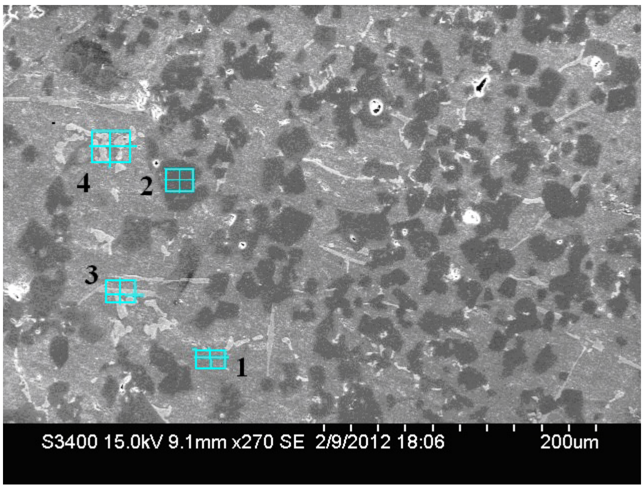
ISBN: 978-988-19252-9-9
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)




(a) Al-28Si alloy




(b) Al-28Si-5Cu-4Fe alloy




(c) Al-28Si-5Cu-4Mg alloy

Fig. 2. Scanning Electron Micrographs of spray formed alloys with EDS.

alloy. The microstructure of spray deposited alloy shows significant differences to cast counterparts, which depicts intermetallic secondary phases containing Cu and Mg in an Al-matrix. The microstructure of alloy exhibits coexisting facetted primary Si particles and fine plates of complex intermetallic phases. The EDS spectrum reveals that the particulates in dark grey contrast contain Si as a major element, light grey contrast plate reveals the intermetallic Q-$Al_{48}Si_{29}Mg_{18}$ and bright white color reveals the $\theta$-$Al_2Cu$ phase(Table V).

TABLE III
EDS RESULTS OF SPRAY DEPOSITED AL-28SI ALLOY

| Location | Point 1 | Point 2 | Point 3 |
|---|---|---|---|
| Composition | $Al_{16}Si_{84}$ | $Al_{99}Si_1$ | $Si_{98}Al_2$ |
| Phase | Eutectic | $\alpha$-Al | Si |
| Al-K | 15.24 | 97.78 | 2.25 |
| Mg-K | 0.13 | 0.11 | 0.00 |
| Si-K | 83.27 | 0.87 | 97.23 |
| Fe-K | 0.12 | 0.05 | - |

TABLE IV
EDS RESULTS OF SPRAY FORMED AL-28SI-5CU-4FE ALLOY

| Location | Point 1 | Point 2 | Point 3 | Point 4 |
|---|---|---|---|---|
| Composition | $Al_{98}Si_2$ | $Al_{67}Cu_{32}$ ($Al_2Cu$) | $Al_{66}Si_{19}Fe_{16}$ ($Al_5SiFe$) | $Si_{99}$ |
| Phase | $\alpha$-Al | $\theta$ | $\beta$ | Si |
| Al-K | 96.17 | 45.84 | 55.75 | 1.37 |
| Mg-K | 0.13 | - | 0.00 | - |
| Si-K | 2.16 | 0.74 | 16.41 | 98.34 |
| Fe-K | 0.00 | 0.31 | 27.09 | 0.30 |
| Cu | 3.94 | 55.03 | - | - |

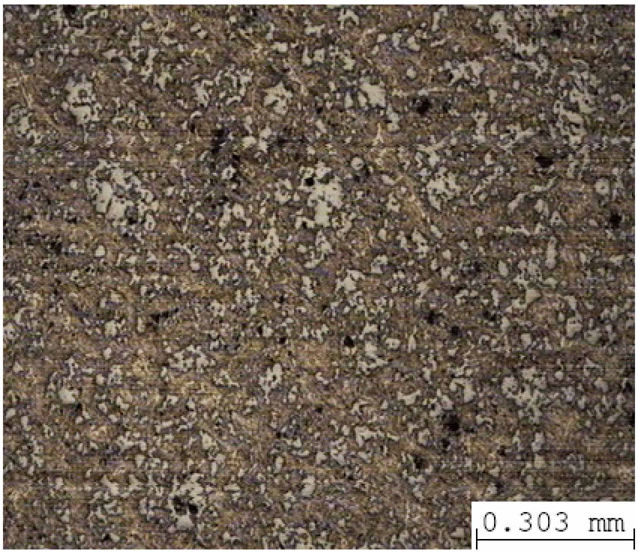
TABLE V
EDS RESULTS OF SPRAY FORMED AL-28SI-5CU-4MG ALLOY

| Location | Point 1 | Point 2 | Point 3 | Point 4 |
|---|---|---|---|---|
| Composition | $\alpha$-Al | $Si_{98}$ | $Al_{48}Si_{29}Mg_{18}Fe_4$ | $Al_{66}Cu_{34}$ |
| Phase | $\alpha$-Al | Si | $\beta$ | $\theta$ |
| Al-K | 92.22 | 0.87 | 45.98 | 44.66 |
| Mg-K | 1.00 | 0.00 | 15.53 | 0.49 |
| Si-K | 1.07 | 98.64 | 28.33 | 1.13 |
| Fe-K | 0.06 | 0.11 | 9.68 | 0.50 |
| Cu | - | - | - | 55.16 |

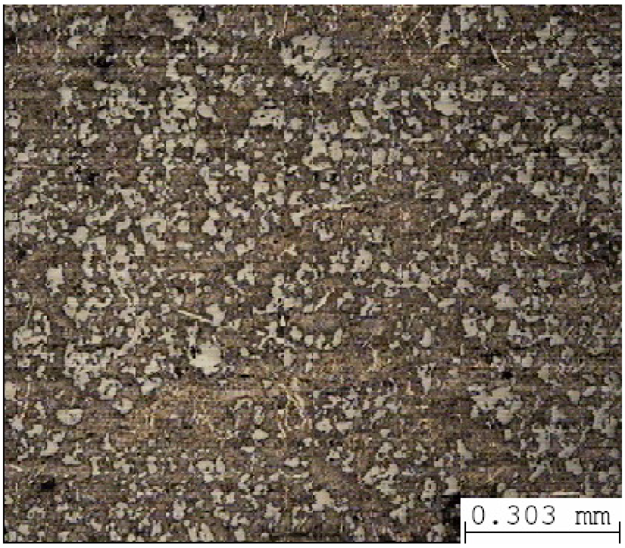
The microstructures of spray formed and hot pressed alloys are shown in Fig. 3. The porosity has reduced to 7, 4 and 5.6 % respectively after hot pressing of spray formed alloys. Further, a finer matrix and enhanced density of the alloys is achieved. Fig. 3(a) depicts fragmentation of Si phase in Al-28Si alloy. Fig. 3(b) shows the microstructure of spray formed and hot pressed Al-28Si-5Cu-4Fe alloy. After hot pressing, the alloy showed partially re-crystallized grains together with elongated grains. However, there was no significant change in the size and morphology of Si particles. Fig. 3(c) shows the micrograph of spray deposited and hot pressed Al-28Si-5Cu-4Mg alloy which depicts fragmentation of Si and brittle $\theta$ and Q intermetallics in the matrix.

The microstructure evolution in spray formed hyper eutectic Al-Si alloys is explained by many researchers [7]. Equiaxed grains and particulate Si structure in spray forming is the result of high cooling rate, fracture and impact deformation during atomization and deposition process. In case of Al-Si-Cu-Fe alloy system, a more complex sequence of phase transformation occurs. It is well known that the sequence of equilibrium solidification events cannot be followed in spray deposited hypereutectic Al-Si-Cu-Fe alloys. It may be assumed that the solidification of spray-deposited Al-Si-Cu-Fe alloy droplets occurred in the following sequence. In the beginning of solidification, metastable $\delta$-$Al_4FeSi_2$ phase is

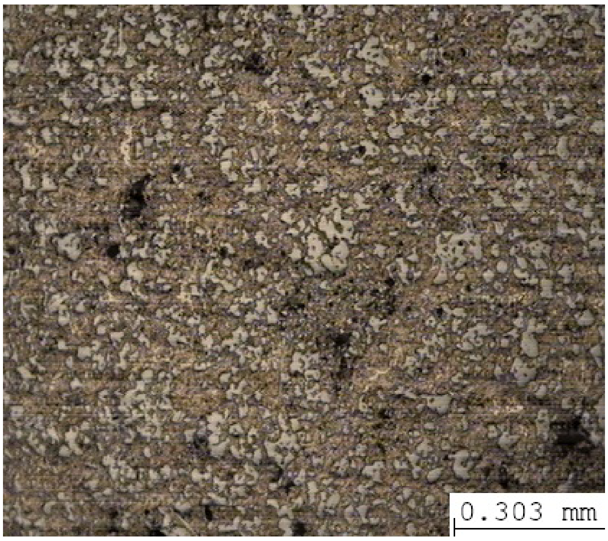
ISBN: 978-988-19252-9-9
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)




(a) Al-28Si alloy




(b) Al-28Si-5Cu-4Fe alloy




(c) Al-28Si-5Cu-4Mg alloy

Fig. 3. Optical Micrographs of spray formed and hot pressed alloys.

crystallized, and then primary Si nucleates on the $\delta$-$Al_4FeSi_2$ phase and grows. Finally, the remaining liquid solidified into an irregular ternary eutectic of $\alpha$-Al, Si, $Al_2Cu$ and $\delta$-$Al_4FeSi_2$ phases. Zhou *et. al.*[8] reported that, except for the Si phases (including eutectic phase and primary Si crystals), the metastable $\delta$-$Al_4FeSi_2$ phase was predominant in the spray deposited microstructure and the volume fraction of the equilibrium $\beta$-$Al_5FeSi$ phase was relatively small. The high volume fraction of metastable $\delta$-$Al_4FeSi_2$ phase in the spray deposited microstructure may be attributed to two primary reasons. First, the tendency of metastable phase formation in alloy is relatively strong. Therefore, extensive precipitation of the $\delta$-$Al_4FeSi_2$ phase should occur during the atomization stage. Second, the kinetics associated with the metastable to equilibrium phase transition in this alloy is relatively sluggish. The reason for the formation of $\beta$-$Al_5FeSi$ phase is associated with the thermal condition of impinging droplets. The solidification process during spray deposition occurs in two stages: gas atomization (rapid cooling) and droplet consolidation (relatively slow cooling). In case of gas atomization, the $\delta$-$Al_4FeSi_2$ phase is able to form within droplets to some extent before deposition. Upon droplet deposition, an abrupt fall in solidification rate occurs within the deposited layer. At this time, the $\delta$-$Al_4FeSi_2$ phase originated from the droplets can be readily transferred into the stable $\beta$-$Al_5FeSi$ phase due to slow cooling (or annealing) effect[2].

Spray formed Al-28Si-5Cu-4Mg alloy contains refined and uniformly distributed Si and intermetallic particles. This can be explained as, the cooling rate increased during atomization, the droplets experience large undercooling prior to nucleation of primary Si phase leading to refinement. Simultaneously, reduced temperature suppressed growth of these phases even after the deposition [9]. Thus, large amount of fine and uniformly distributed Si and greater number of precipitates ($Al_2Cu$ phase, Q phase) are seen in the spray deposited alloy. The dendritic structures as well as the Chinese script structure observed in the as-cast materials are modified and it is difficult to discern the difference between primary $Al_2Cu$ and Q phases.

Hot pressing of spray-formed alloys leads to reduction in porosity, grain recovery and recrystallization to a certain extent. The preheated treatment before compression process can make the microstructure more uniform. Secondly, hot deformation leads to a microstructural refinement and a 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 forms lot of small angle grain-boundaries, refining initial grains into several substructure [10]. In addition to the refinement of grains, hot deformation also promotes homogeneous precipitation and hardening of $\theta$ phase and Q phase which can pin the movement of dislocations to restrain grains coarsening during recrystallization effectively.

### B. *Mechanical properties*

The results of room temperature tensile properties of as cast and spray deposited hot pressed Al-28Si, Al-28Si-5Cu-4Fe and Al-28Si-5Cu-4Mg alloys are listed in Table VI. The results show that the spray formed hot pressed alloys exhibit considerable improvement in their tensile strength compared to their cast alloys. The SF+HP Al-28Si-5Cu-4Fe alloy exhibits the highest strength and % elongation

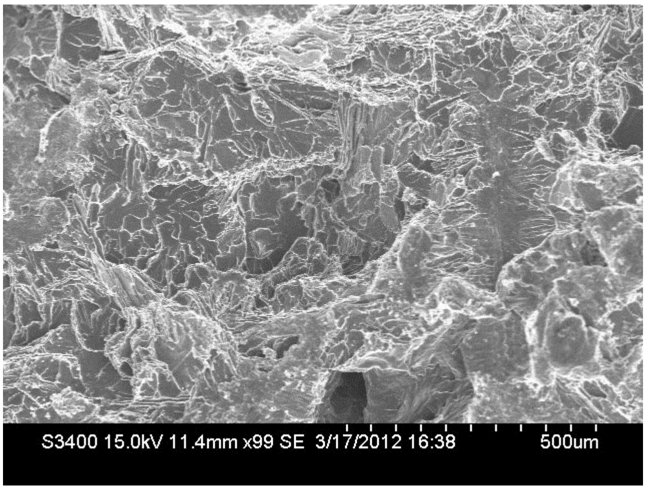

ISBN: 978-988-19252-9-9
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

compared to Al-28Si and Al-28Si-5Cu-4Mg alloys. The SEM fractographs of SF+HP Al-28Si, Al-28Si-5Cu-4Fe and Al-28Si-5Cu-4Mg alloys are shown in Fig. 4. All fractographs indicate brittle failure characterized by the facet nature of the fractured surfaces. Fig. 4(a) shows fracture surface of spray formed hot pressed Al-28Si alloy. It is composed of numerous micro voids, fine microscopic cracks and a few large dimples which are associated with the primary Si particles. Fracture is observed to originate at the specimen surface where localized, typical brittle fracture features are observed. Fig. 4(b) shows the SEM fractograph of spray formed hot pressed Al-28Si-5Cu-4Fe alloy. The fracture surface shows several microvoids and fine microscopic cracks which are associated with the primary Si and intermetallic phases along with under developed ductile dimples. This feature suggests a combined ductile as well as brittle fracture mode. Fig. 4(c) shows the tensile fracture surface of spray deposited hot pressed Al-28Si-5Cu-4Mg alloy. The fracture surface of this alloy clearly shows the presence of large facets and numerous dimples of about only 2-5 $\mu$m indicating quick connection of the microvoids, suggesting brittle fracture with significantly reduced elongation. The presence of fine and uniformly distributed $Al_2Cu$ precipitates in the matrix, serve as the nucleation site for voids, reducing the resistance of the cavitation in the matrix and also causing the connection of microvoids in a shorter interval of time. Both of these effects decreased the ductility significantly.

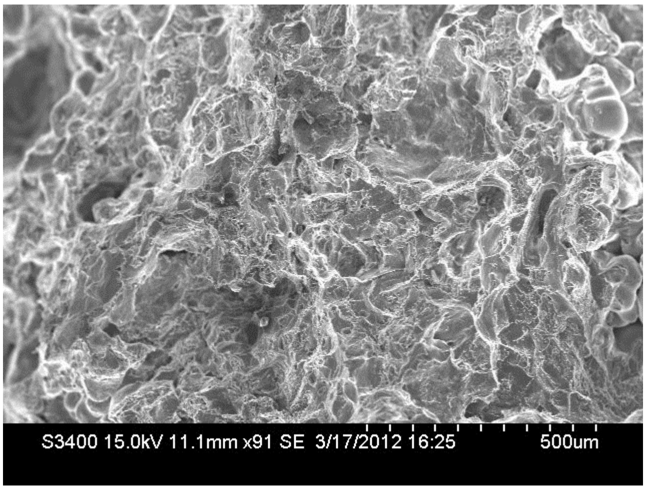
TABLE VI
PROPERTIES OF AS CAST AND SPRAY FORMED HOT PRESSED ALLOYS

| Alloy | Processing route | YS (MPa) | UTS (MPa) | Total elongation (%) |
|---|---|---|---|---|
| Al-28Si | As cast | 40 | 43 | 1.67 |
| Al-28Si | SD+HP | 149 | 172 | 7.2 |
| Al-28Si -5Cu-4Fe | As cast | 143 | 163 | 6.53 |
| Al-28Si -5Cu-4Fe | SD+HP | 278 | 356 | 16.67 |
| Al-28Si -5Cu-4Mg | As cast | 56 | 87 | 2.78 |
| Al-28Si -5Cu-4Mg | SD+HP | 172 | 255 | 5.73 |

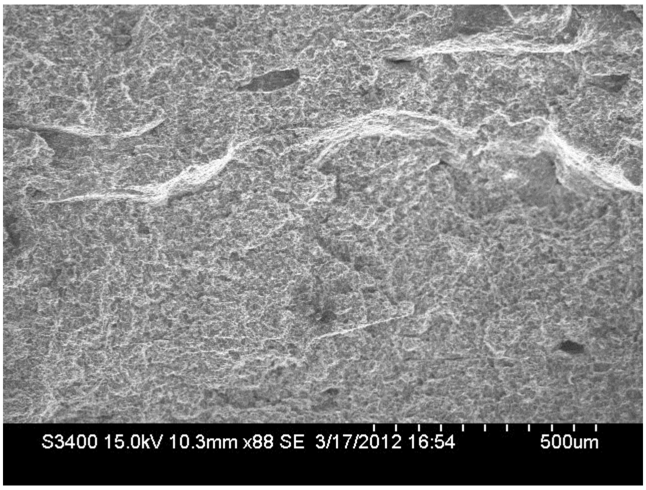
The improvement in strength of spray formed hot pressed alloys may be attributed to the refinement in microstructure and uniformly distributed primary Si particles and fine intermetallics. Further, the spray formed hot pressed alloys do not possess the connected brittle secondary phases and therefore it could withstand considerable amount of plastic deformation prior to fracture resulting in improved ductility [11]. On the contrary, the cast alloys showed lower values indicating the brittle failure of the alloys. The premature failure and low ductility of as cast alloys may be due to the possibility of crack initiation at Si/Al matrix interfaces. The low tensile strength and ductility in as cast Al-28Si-5Cu-4Fe alloy compared to its spray formed hot pressed alloy is mainly due to presence of Fe-containing intermetallics in needle shape. Under tensile load Fe containing intermetallics ($\beta$-phase) are much more easily fractured than the aluminium matrix or the silicon particles. Micro-cracks tend to initiate at these particles and they provide easy pathways for cracks to propagate through. It has been reported that the intermetallic phases may act as stress raisers and crack initiation sites. Further, due to the lack of active slip systems in the intermetallic compounds the ductility of the alloy gets reduced [12].




(a) Al-28Si alloy




(b) Al-28Si-5Cu-4Fe alloy




(c) Al-28Si-5Cu-4Mg alloy

Fig. 4. Scanning Electron fractographs of spray formed and hot pressed alloys.

During tensile testing of as-cast Al-28Si-5Cu-4Mg alloy, damage appears by cracking of the plate shaped $\theta$ and Q phases at small plastic strain. During strain progressing, small cracks and also some voids occur along the interfaces of Si-Al. Further, these defects coalesce to generate a crack that propagates along the Si particles. These cracks may offer less resistance to their propagation than the cracks in the

ISBN: 978-988-19252-9-9
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

coarse Al matrix. As a result, the as-cast alloy generally fails along the $\theta$ and Q plates under tensile stress without considerable elongation to failure and mainly shows brittle fracture mode [13]. The typical dendritic microstructure of the as cast alloy with existence of Si phase in sharp edged plate-like particles and Q and $\theta$ phases in vermiform and long acicular shapes with uneven distribution in $\alpha$-Al matrix, can terribly be teared because of stress concentration and hence, results in decrease in the tensile strength of as cast alloy [14].

## IV. Conclusions

Spray forming is effective in refining the microstructures of Al-28Si, Al-28Si-5Cu-4Fe and Al-28Si-5Cu-4Mg alloys. Hot pressing of spray-formed alloys leads to reduction in porosity, grain recovery and recrystallization to a certain extent. Spray deposited Al-28Si-5Cu-4Fe and Al-28Si-5Cu-4Mg alloys contain fine, uniform distribution of primary Si and precipitation strengthening $\theta$-$Al_2Cu$ phases along with $\beta$-$Al_5FeSi$ and Q-$Al_{48}Si_{29}Mg_{18}$ intermetallic phases respectively. The room temperature tensile tests of spray formed hot pressed alloys showed significant increase in ultimate tensile strength compared to as cast alloys. Spray formed hot pressed Al-28Si-5Cu-4Fe alloy exhibited superior ultimate tensile strength and significant increase in elongation to fracture compared to other alloys.

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ISBN: 978-988-19252-9-9
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)