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Spray Deposition Process of Hypereutectic Al – Si alloys: An overview

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Abstract—Modified Al alloys are gaining emphasis in the past few years due to wide range of properties available for the engineering applications. These alloys are manufactured by spray forming process have superior properties over the conventional cast alloys. Hence in this article an attempt has been made to summarize the work that has been carried out in the field of spray forming of hypereutectic Al – Si alloys and with other alloying elements such as Fe, Cu, Mg and Mn. As hypereutectic Al – Si alloys are attractive for the industrial applications due to their low thermal expansion co – efficient and high tribological properties. In this study attention has been paid towards the microstructure, mechanical and tribological properties of the studied alloys. The study of process parameters over the size and shape of the powder in spray forming is other part of this work. The change in properties of spray formed alloys by the working of secondary process is also been considered.

Index Terms— Hypereutectic Al – Si alloys, Spray deposition, Microstructure, Secondary process.

1 INTRODUCTION

IN document is a template for Microsoft Word versions the present scenario Al alloys are gaining more importance in engineering applications like aerospace, automobile, etc., due to its wide range of physical, mechanical and tribological properties [1]. However conventional cast materials exhibits poor properties compared with spray formed materials [2]. Previous literatures have shown that the particle size, microstructure and mechanical properties are good when Al based alloys are manufactured by spray deposition process [3 – 6]. Gupta and Lavernia [7] studied the microstructure of hypereutectic Al – 17Si – 4.5%Cu alloy and their analysis revealed that spray atomization and spray deposition processing leads to significant refinement of microstructure as compared to its as cast counter part. They observed the microstructure characteristics as follows: (a) an equiaxed grain size (b) unconverted porosity (c) nearly spherodized secondary phases.

2 SPRAY DEPOSITION PROCESS AND PROCESS VARIABLES

Spray deposition process is one of the rapid solidification processes to produce new material by controlling the microstructure. The schematic representation of the spray deposition process is shown in Fig. 1. During the process, melt is atomized by transfer of high kinetic energy from gas to melt and melt droplets are collected on substrate, process variables like gas to melt ratio (G/M), melt superheat and atomizer design affects the size and size distribution of droplets during atomization [8 - 9]. Thus it finds necessary to understand the effect of process variables.

Jeyakumar et al. [10] studied the influence of process parameters and characteristics of Al alloys spray deposition process. They reported that powder size decreases with the increase in the applied gas pressure and also the yield, the result is also similar for decrease in the flight distance. A number of models were proposed by many literatures which relates the particles size and standard deviation which is specific for the particular nozzle designs [11 - 13].

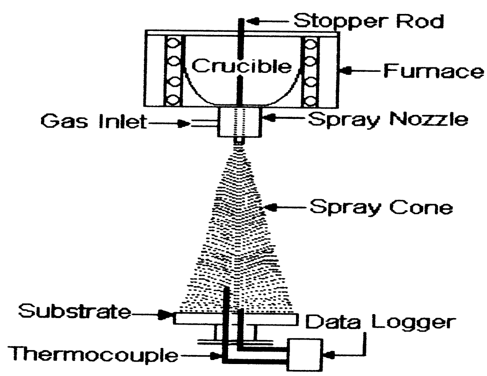

Figure1 showing representation of spray deposition process

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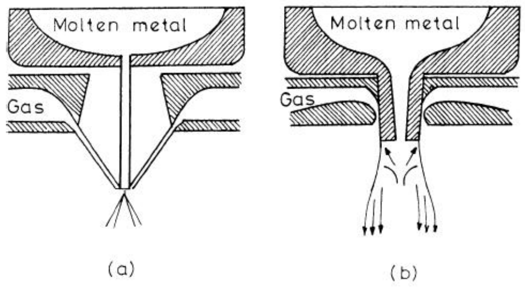

Fig. 2 Design of atomizers (a) free fall nozzle (b) closed couple nozzle [15]

Srivastav and Ojha [14] reported that G/M plays an important role in determining the particle size, standard deviation and flake formation. The productivity also increases with decrease in standard deviation for a given range of particle size. Singh et al. [15] found that the pressure supply by the given amount of gas for atomisation of freely falling molten metal stream based on an empirical formulae. They considered limiting velocity and plenum pressure and proposed models as equations (1) and (2) for the free fall atomizer designs (Fig. 2).

$$P_L = 9.24\times10^6 \rho^{0.3} F^{1.43} \alpha^{-0.97} \qquad \text{............(1)}$$

$$V_L = 2.7\times10^3 \rho^{0.22} L^{0.62} \alpha^{-0.93} \qquad \text{............(2)}$$

The benefits of spray deposition process are fine microstructure, enhanced mechanical, physical and tribological properties and also facilitate to produce composites with greater extent of uniform distribution. Srivastav et. al. [16] reported that there was considerable fine refinement of microstructure produced by spray forming compared to as cast alloys (Fig. 3 and Fig. 4). However the low efficiency, porosity in the material and material loss during the process are its limitations. The applications of spray deposited alloys and composites include automotive, aerospace, electrical and electronics applications. The bearing materials are also being manufactured by spray formation as it provides better tribological properties.

These alloys are attracted the researchers and industries as it provides excellent properties such as specific strength and modulus with low co-efficient of thermal expansion and good wear resistance. It is difficult to produce such alloys by conventional casting process [17 - 18] and maximum possible addition of silicon by casting is 22 - 24% [19]. However it is possible to produce hypereutectic Al - Si with greater than 25% Si by spray forming and microstructure evolution of hypereutectic Al-Si alloys by spray forming is shown in Fig. 5 [20].

In spray forming process of hypereutectic Al - Si alloys, when the diameters of nozzle increases as G/M ratio decreases and vice versa. The increase in G/M ratio leads to the fall in the size of the primary Si phase from 5 - 10 to 2 - 5μm, because the cooling rate is being enhanced during the flight time. Primary Si phase is recrystallised from the melt and develops a variety of regular polygon shape and spherical shape particles. The size of the primary Si phase also increases with the increase in preheating temperature [21]. Ha et al. [23] produced Al - 25%Si alloy by spray forming, the Si particles are uniform size and distribution. This study revealed that strain rate sensitivity factor is very low 0.1 below 300^0C and reaches maximum value to 0.2 at 500^0C from a series of load relaxation and compression test. The fine Si particle size production is possible in spray forming due to its higher cooling rate, which enhances the toughness of the alloy [24].

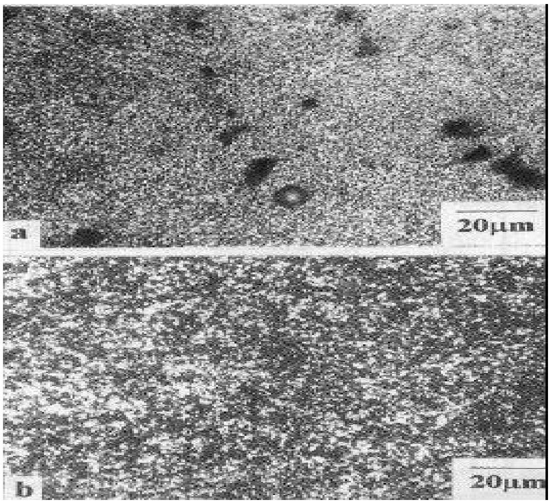

Fig. 3 Microstructure of spray-deposit near the substrate showing a. porosity and b. fine scale microstructure of second phase particles [16]

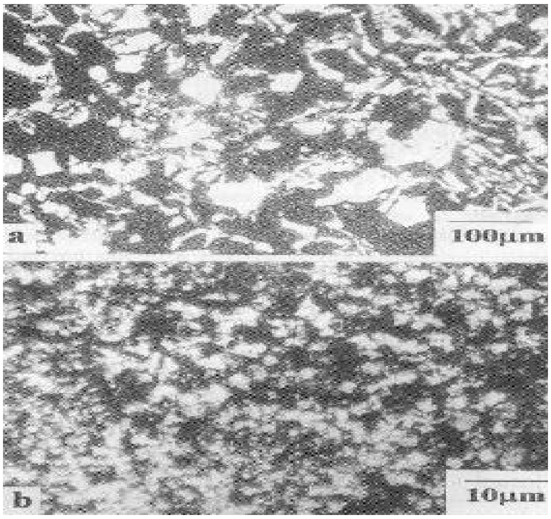

Fig. 4 Microstructure of the alloy showing a. coarse particles in the as cast alloy and b. fine second phase particles in spray-deposit [16]

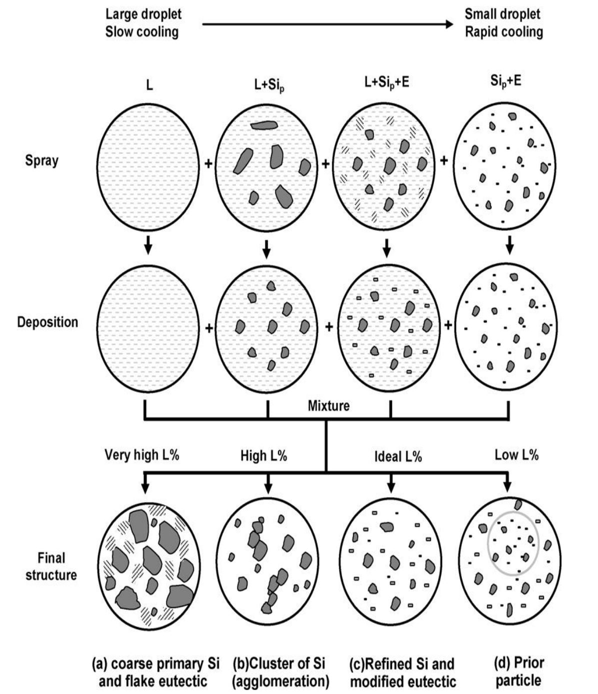

Fig. 5 Microstructure evolution of hypereutectic Al–Si alloys in spray forming [19]

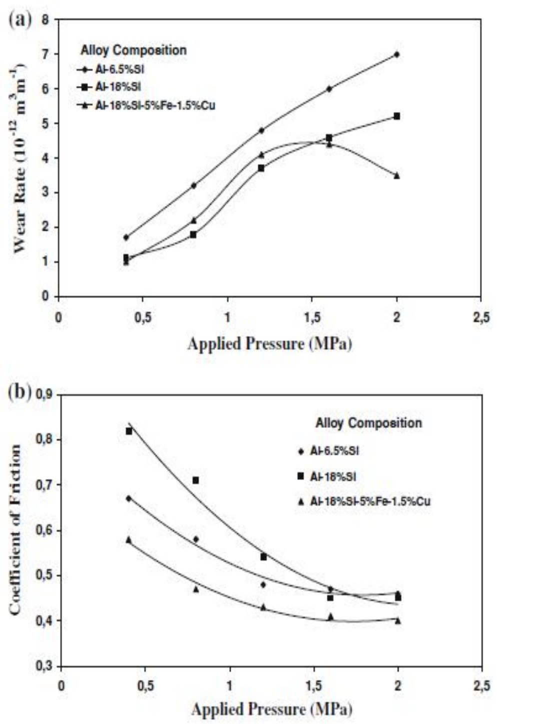

Fig. 6 Variation of (a) wear rate and (b) coefficient of friction with applied pressure for spray formed Al-Si alloys (constant sliding velocity of 1.44m/s) [28]

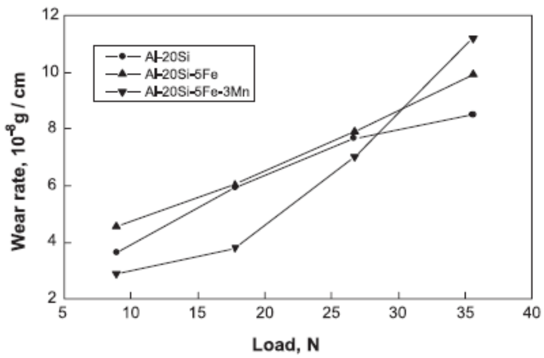

Fig. 7 Variations in the wear rates of spray deposited Al-Si alloys with load [1]

A comparative study shown that Al - 70%Si and Al - 60%Si exhibits the average density of 2421 $kgm^{-3}$and 2465 kgm^{-3}, average ultimate flexural strength of 180Mpa and 220Mpa and with the hardness 261 and 162 BHN respectively [25]. An another study has shown that Al - 25%Si exhibited 164MPa ultimate tensile strength (UTS) with 14.8% elongation, elastic modulus as 88.4 GPA and specific modulus as 3.4 x 10^9 mm [26]. Kim et al. [27] demonstrated that Al - 25%Si alloy almost behaves like superplastic Al - matrix at elevated temperature and has obtained 250% maximum tensile elongation, at 5 x 10^{-4} S^{-1} and at 500^0C. Extensive viscous formation was another observation of this study. They have concluded that liquidation of grain boundary material during grain boundary sliding may be responsible for the result.

The tribological characteristics of hypereutectic Al – Si alloys is better than the hypoeutectic alloys. Al – 18%Si shown very good wear behaviour than the Al – 6.5%Si. As the applied pressure increases, the wear rate increases. However, the hypereutectic alloy has shown less wear rate in all condition of applied pressure compared with hypoeutectic alloys (Fig. 6) [28]. It has been shown that as the applied load increases, the wear rate increases rapidly (Fig. 7) [1]. As the sliding distance increases, the wear volume increases and was very high at sliding distance greater than 1000m [29]. Elmadagli et al. [30] studied the microstructure and wear resistance of Al – Si alloys. They compared wear characteristics of as cast 383 alloy, A390 with spray formed Al-25Si alloys and reported that there was an increase in wear resistance and transition load considerable with increase in the Si content (Fig. 8-10). It can be also soldered without any difficulty [23]. Thus it provides a wide range of properties for a numerous engineering applications

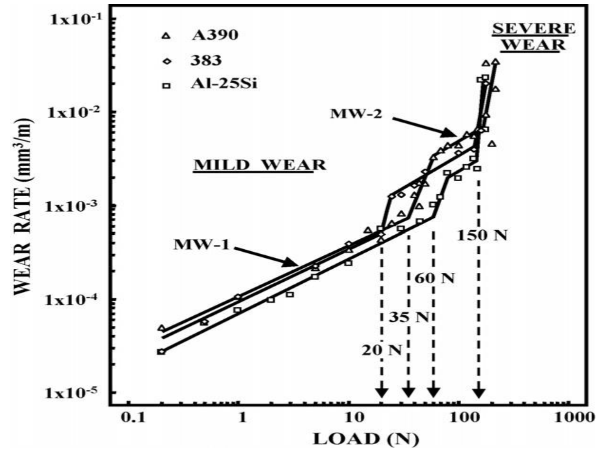

Fig. 8 Wear rates of the as-received A390, 383 and Al–25Si alloys plotted against load on a logarithmic scale. The two sub-regimes of mild wear MW-1 and MW-2 are separated by a transition regime. The loads 20, 35, and 60N correspond to the highest load inMW-1. The transition fromMW-2 to the severe wear regime occurs at 150N for all the alloys [30]

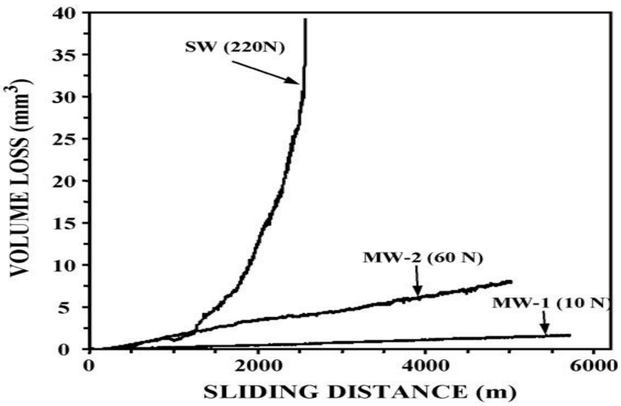

Fig. 9 Volume loss vs. sliding distance plots of the A390 in mild wear regime (MW-1:10 N,MW-2: 60 N) and severe wear regime (SW: 220 N) computed from height changes of the samples [30]

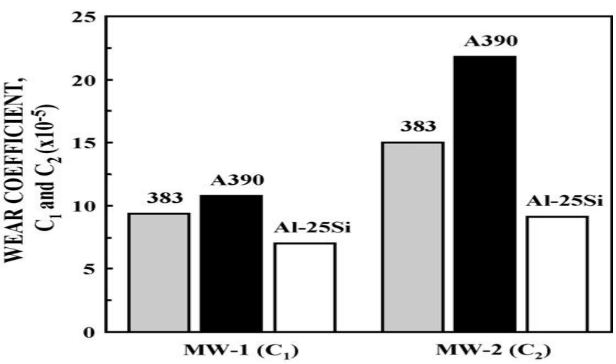

Fig. 10 Comparison of the wear coefficients of the as-received alloys. The wear coefficients (C1) of MW-1 and (C2) of MW-2 reflect the differences in the wear rates of the alloys [30]

3 HYPEREUTECTIC AL-SI TERNARY ALLOYS

3.1 Effect of Fe addition on the properties of Al – Si alloys

Eventhough Al – Si alloys is providing a wide range of properties, a new emphasis was aroused in the fast few years that to give an additional requirement at high temperature stability and microstructure. Accordingly Fe is one of the additive to the Al – Si alloys which results in stable intermetallic phase but the limitation is, in conventional casting due to slow cooling rate segregation of microstructure and hence porosity forms [31 – 33]. A study has revealed that Al – 5%Fe alloys exhibits drastic refinement and modification in the microstructure with a uniform distribution of secondary phase particles in the matrix [29]. In another phenomenon, during solidification at high undercooling it may form several dispersoids of Al_xFe [34].

Thus phase and microstructure of alloys are highly influenced by the duration of undercooling and concentration of Fe [34 – 36]. Islas et al. [37]studied the solidification of microstructure of Al – Fe binary alloys and reported that the content of Fe in the α – Al phase alloys increases with decrease in powder size and undercooling increases with increasing cooling rate and decreasing with the size of atomized powders. The addition of Fe to the Al – Si alloys reveals better development in the properties of Al – Si alloys. But it is difficult to produce by conventional casting, because of the formation of large size Si phase and vary plates of Al – Fe. However it is possible to cast Al – Si – Fe alloys adequately by spray deposition [38 – 45]. Srivastav et al. [3] produced Al – Fe alloys by spray deposition with uniform distribution Al_3Fe phase and Al – Fe alloy exhibited ductile mode of fracture compared to mixed mode of fracture of Al – 18Si alloys under tensile loading and was found to be 19% elongation of Al – 5Fe alloy.

3.2 Effect of non ferrous alloying elements addition on the properties of Al – Si alloys

Blockford et al. [46] produced Iron Aluminide preform by spray forming and found that spray deposited layer exhibited some oxide and porosity. However porosity decreased with heat treatment. A layer of Fe_2O_3 was noticed in this study instead of Al_2O_3 layer, which is usually found in Al binary alloys. Wang et al. [1] and Srivastav et al. [4] reported that addition of 5% Fe to Al – 20Si results in the formation of needle shaped intermetallic phase (Fig. 11-12). Wang et al. [11] also studied the wear characteristics as follows. At lower loads Fe containing alloy showed higher wear rate compared with Al – 20Si alloy due to tendency for embrittlement because of needle shaped intermetallic and even at higher loads Fe containing alloy exhibited inferior wear resistance than the binary alloy due to fragmentation at intermetallics, result-

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ing in crack nucleation and propagation. Wear process is controlled by subsurfaced cracking assisted by sliding mechanism.

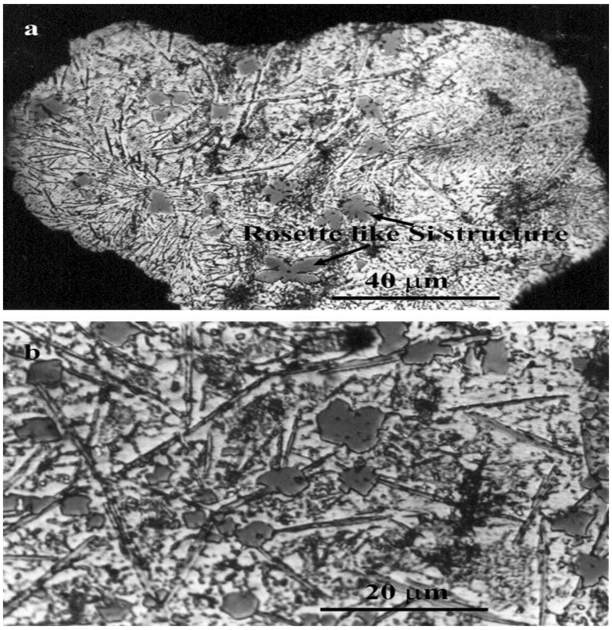

Fig. 11 Optical micrographs of a section of oversprayed powder particles showing: (a) facetted and needle-shaped morphologies of primary Si and intermetallics and (b) rosette-shaped morphology of Si. [4]

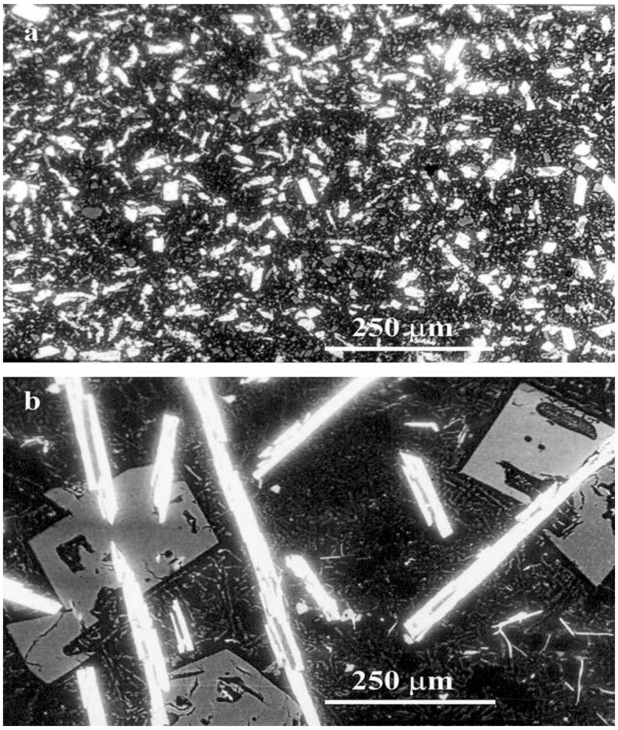

Fig. 12 SEM backscattered images showing: (a) microstructure of spray deposited alloy showing primary Si phase along with refined intermetallics and (b) microstructure of conventional as-cast alloy. [4]

Leo et al. [47] reported that there was an internal friction in the temperature range of 50 – 250^0. In spray deposited Al – 3.3Fe – 10%Si alloy. Perhaps due to influence of $FeAl_2$ boundary relaxation and also affected by Al – Fe – Si intermetallic particle at the grain boundary. Mocellian et al. [48] reported that there was damage in the tensile loading of T_4 temperature alloy due to cracking of Si primary particles and is associated with the loss of elastic modulus. As the applied stress increased, the silicon particles are broken because a critical tensile stress level is reached within the critical applied stress value, the stress value at which silicon particles are broken depends on the parameters such as internally induced stresses and also stress concentration effect due to plastic deformation in the Al – alloy matrix around the silicon particles, the stress concentration factor is generally reduced by decrease in grain size and internally induced stresses, corresponding to a compressive stress tied in one silicon and particles delays the beginning of damage.

Addition of Fe provides high diffusivity in liquid state and low diffusivity in solid state [49 – 51], which ensures chemical homogeneity in one α – Al matrix and its thermal stability, in both processing service. Iron has an extremely low equilibrium solid solubility in α – Al at room temperature under the condition of rapid solidification [51]. Enhancement of the mechanical properties of the Al base alloys can also be done by the addition of Cu, Mg. The addition of Cu and Mg to the Al – Si alloys may form the precipitation producing phases such as Al_2Cu, Mg_2Si, Al_2CuMg [51 – 55]. Both Cu and Mg act as precipitation hardening elements and their strengthening effect is dimished at above 150^0C because of low thermal stability of the precipitates [49].

Kai et al. [56] produced Al2024 alloy by spray deposition and reported that there was an increase in the porosity of the alloy. Srivastav et al. [25] reported that the microstructure of Al – 305Cu – 10Si alloys exhibited equiaxed grain morphology of one primary α – phase with particulate morphology of Si particles located at the grain boundaries and finer Si particles in the grain interior. Addition of 1.5%Cu to Al - 18Si – 5Fe reveals the microstructure with uniform distribution of primary Si phase and intermetallic compounds such as β – Al – Fe – Si and δ – Al_4Si_2Fe phases [25, 57]. Santos et al. [58] studied the corrosion performance of Al – Si – Cu hypereutectic alloys in synthetic condensed automotive solution and their results revealed that the preferential attack of Al matrix phase in all their studied alloys. The alloy with higher Cu content and prepared by spray forming was more susceptible to pitting compared to other alloy.

Jodoin et al. [59] reported that conventional nanocrystalline Al2618 alloy coatings sprayed on to Al substrate using cold gas dynamic spraying process exhibited negligible porosity and excellent interface with the substrate material in the range of 5 to 10% and morphology of obtained powder particles is shown in Fig. 13. Ikram [60] studied that microstructure of Al – 6Si – 1.9Cu – Mg alloys and found that harndness was increased by increasing Mg content except for 1.13% Mg alloy aged for 10hrs and Q phase particles are perhaps responsible for the trend of hardness. The microstructure and mechanical properties of spray formed and squeeze cast Al – 25Si – 0.8Cu – 0.84Mg alloys was studied and compared by Chiang and Tsao [2] observed that spray formed alloy has higher degree of super saturation than that of squeeze cast alloy and peak aged spray formed alloys exhibited ultimate strength of 366MPa yield strength of 235.3MPa and elongation of 3.4%. The study of Wang et al. [1] revealed that addition of Mn to Al – 20Si – 5Fe alloy reduced the wear rate at lower loads of about 25N and has got increased than that at higher loads of about 35N.

Estrada and Duszczyk [61] studied the characteristics of rapidly solidified spray deposited Al – Si – X preforms and concluded that Al alloy can be spray deposited without oxide films and with fine precipitates. The deposited matrix exhibited an average porosity level as low as 1.3% and the porosity was uniform throughout preform and microstructure does not depends on the small local porosity variation. Thus addition of non ferrous alloying elements with Fe to the hypereutectic Al – Si alloys enhances the microstructure, mechanical and tribological properties.

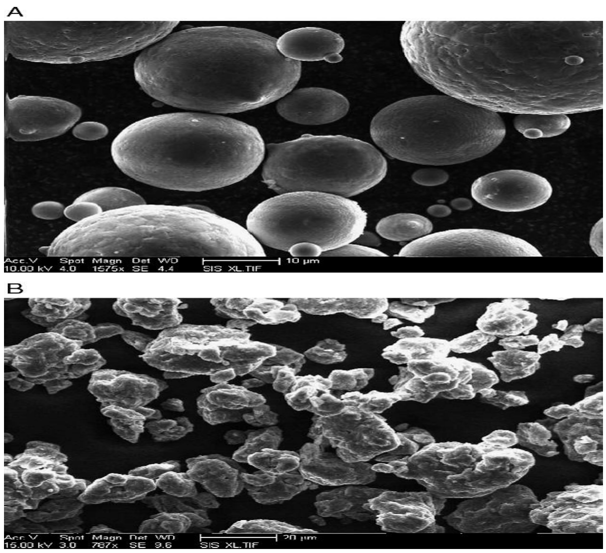

Fig. 13 Morphology of powder A) as atomized B) as cryomilled [59]

4 Effect of Secondary Processing on the Properties of Al – Si Alloys

Eventhough spray atomization provides better microstructure and enhanced physical properties than as cast alloys. There is a problem with the formation of intermetallic phases with the needle shaped and having relatively large size in α matrix. This may also induce detrimental effect on the mechanical and tribological properties on the final product [49]. It also affects on the effectiveness at stabilizing the microstructure, hence it is desired always to do the post atomization process. It leads to the decrease in their size and interspacing often heat treatment can be done but it cannot complete the necessary requirement. Since intermetallic cannot be resolved in the solid matrix. The principle advantages of secondary process are refinement of the microstructure and reduce the porosity of the deposit.

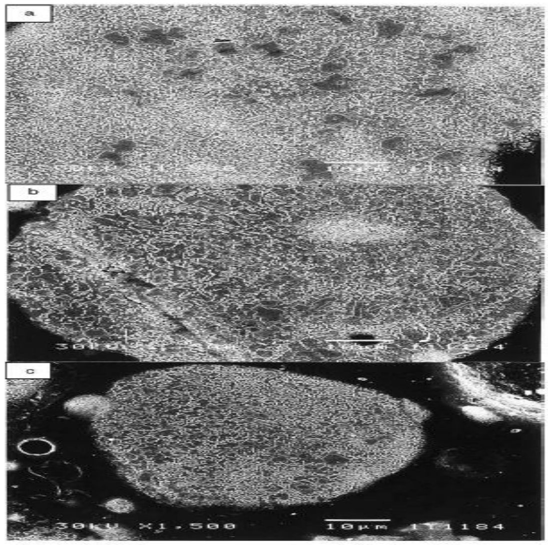

Fig. 14 SEM micrographs of gas-atomized Al–20Si powder particles with different sizes (a) 90–106 mm, (b) 75–90 mm, and (c) 45–53 mm [62]

Extrusion itself is a complicated thermomechanical process [7]. Hong et al. [62] observed that due to severe shear deformation takes place during hot extrusion. The large eutectic structure and primary Si phase and were fragmented into smaller particle and distributed homogenously in the Al – matrix (Fig. 14). Seok et al. [25] found that spray formed and extruded Al – 25Si has properties as follows UTS – 164MPa, elongation – 14.3%, elastic modulus – 88.4GPa and specific modulus 3.4 x 10^9mm. Cui et. al. [63] studied the characterization of Si phases in spray formed and extruded hypereutectic Al – Si alloys and concluded that extrusion plays a role on the interparticles spacing according to the particle grooves or fragmentation mechanism. The Si particles in extruded Al – Si alloys appear more homogenous and regular than as deposited but with a certain amount of anisotrophy and tendency to preferred orientation (Fig. 15 and 16). Ha et. al. [22] has reported that there was refinement of microstructure after extrusion (Fig. 17). Baiqing et al. [64] concluded that high extrusion ratio refines the primary Si phase in microstructure simultaneously, it refills microcracks (Fig. 18). Thus in almost previous literatures secondary processing has been done to refine the grain structure and enhance their characteristics. The Table 1 gives

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the brief comparison of properties of different alloys considered in previous studies.

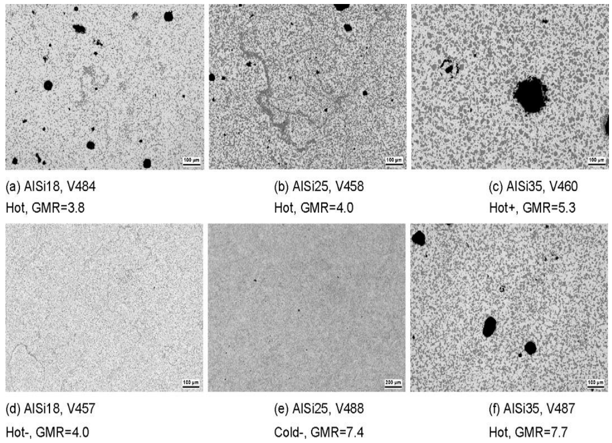

Fig. 15 Porosity in spray formed hypereutectic Al–Si alloy billets. (a) AlSi18, V484 Hot, GMR= 3.8; (b) AlSi25, V458 Hot, GMR= 4.0; (c) AlSi35, V460 Hot+, GMR= 5.3; (d) AlSi18, V457 Hot−, GMR= 4.0; (e) AlSi25, V488 Cold−, GMR= 7.4 and (f) AlSi35, V487 Hot, GMR= 7.7 [63]

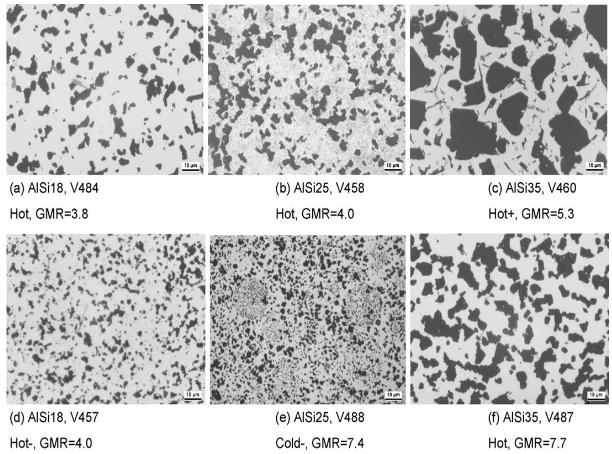

Fig. 16 Silicon precipitations in spray formed hypereutectic Al–Si alloy billets. (a) AlSi18, V484 Hot,GMR= 3.8; (b) AlSi25, V458 Hot,GMR= 4.0; (c) AlSi35, V460 Hot+,GMR= 5.3;(d) AlSi18, V457 Hot−, GMR= 4.0; (e) AlSi25, V488 Cold−, GMR= 7.4 and (f) AlSi35, V487 Hot, GMR= 7.7 [63]

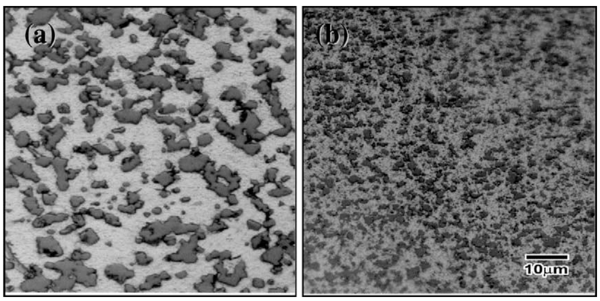

Fig. 17. Typical microstructures taken (a) before and (b) after the extrusion [22]

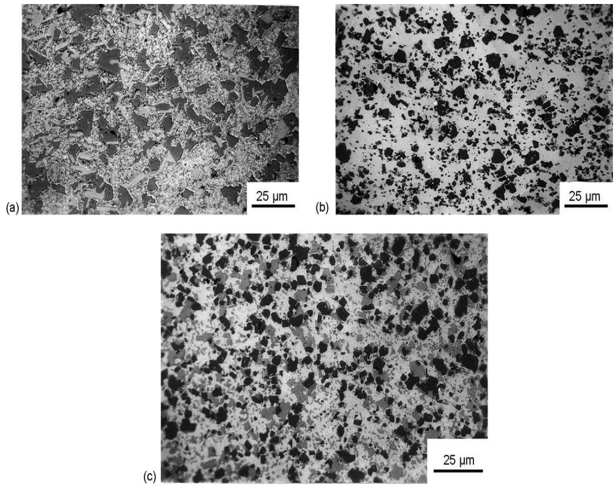

Fig. 18 Micrographs of billets extruded at different extrusion ratios (Ø ¼ 3.8 mm): (a) 10:1; (b) 14:1; (c) 28:1. [64]

5 CONCLUSIONS

In the present study, the previous works on the microstructure, mechanical and tribological properties of spray deposited hypereutectic Al – Si alloys are summarized. On this basis following conclusions were drawn.

- Good amount of work has been carried out related to the study of particle size and morphology of powder produced during spray deposition process. The works has paid concentration on the process variables and nozzle design. There is necessity of relation which provides the relation between the process variables and particle size and morphology for the general nozzle designs. Inspite optimization of process parameters is also vital.
- Hypereutectic Al – Si alloys produced by spray deposited is well studied in consideration of their properties. Yet study is going on corresponding to grain refinement and development of properties with high Si content.
- The development of fine grain and with high wear resistance would be lucrative to aerospace and automotive applications.
- In recent years researchers are concentrating towards the addition of ferrous and non ferrous alloying elements to hypereutectic Al – Si alloys which intensifies alloy properties.
- Secondary processes are also being carried out in supplement with spray deposition process. Since the probability of the presence of porosity in the microstructure of spray deposited alloys, resulting in deteriorated effect on its characteristics. Thus to augments the mechanical properties by decreasing the porosity, generally hot extrusion is processed in

TABLE 1
COMPARISON OF THE PROPERTIES OF CAST AND SPRAY DEPOSITED ALLOYS STUDIED IN PREVIOUS LITERATURES

Alloy	Processing route	Yield Strength (MPa)	UTS (MPa)	Elongation (%)	Hardness	Elastic Modulus (GPa)	Reference
Al – 18Si	AC		50	<3	50HV		[3]
Al – 18Si	ACE	97	129	7	41HV		[3]
Al – 18Si	SDE	120	158	19	59HV		[3]
Al – 5Fe	AC		48		17HV		[3]
Al – 5Fe	SDE	176	201	23	59HV		[3]
Al – 18Si – 5Fe – 1.5Cu	AC		55	<3	53HV		[3]
Al – 18Si – 5Fe – 1.5Cu	SDE	221	262	8	89HV		[3]
Al – 25Si – 0.89Cu – 1Ni – 0.84Mg	SDE	108.9 (Proof stress)	262.9	7.2			[2]
Al – 25Si	SDE		164	14.8		88.4	[22]
Al – 25Si – 3.67Cu – 1.11Mg – 0.4Fe	SDE		420	0.8		88.6	[22]
Al – 17.48Si – 3.67Cu – 0.42Fe – 1.11Mg – 0.02Ni	SDE		305.8	3.5			[20]
Al – 17Si – 3Fe	SDE	400	470	13			[6]
Al – 21Si – 3Fe	SDE	410	473	0.8			[6]
Al – 25Si – 3Fe	SDE	440	503	0.6			[6]
DISPAL S220*	ACE	95	165	2.5	65HV	85	[65]
DISPAL S250*	ACE	205	334	2.7	105HV	95	[65]
DISPAL S260*	ACE	180	265	1.0	110HV	85	[65]
DISPAL 220*	SD	135	230	2.5		86	[65]
DISPAL 240*	SD	425	490	1.5		99	[65]
DISPAL 250*	SD	438	490	1.2		97	[65]
DISPAL 260*	SD	240	360	2.1		98	[65]
DISPAL 260*	SD	180	245	1.2			[65]

*DISPAL is a trade name of PEAK Werkstoff GmbH, Velbert, Germany

the previous literatures

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