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Spray forming of aluminum alloys and its composites: an overview

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Abstract In this article, the work that has been carried out in the area of spray forming of aluminum alloys and its composites has been summarized. The developments that had taken place in the past two decades in this area have been presented. Most of the researchers have investigated on the microstructural properties of these alloys and their composites. In this article, main emphasis was given to the microstructures, wear characteristics, and mechanical properties of as-cast and as-sprayed aluminum alloys. Also, this article is designed to provide the microstructures of as-cast and as-sprayed aluminum-15% silicon alloy. The microstructure of as-sprayed alloy has invariably indicated equiaxed grains throughout the deposit and has been observed that the Si particles are uniformly distributed in the Al matrix. Spray forming offers a combination of low cost manufacturing with enhanced properties and performance. As such it has emerged as a key competitor for existing technologies such as conventional casting, ingot metallurgy, and powder metallurgy.

Introduction

Due to cut throat competition in the global market, rapid changes are taking place in the manufacturing sector. High tech industries are coming up with brand new and efficient manufacturing processes. The aim of any such process is to produce a component economically to a near net shape preform in less time. Although the metal casting process produces a component with a reasonably good quality, it lacks in providing a fine grain structure in the cast product severely limiting its application in critical service conditions. To impart a fine grain structure to a cast product, a number of secondary processing operations like rolling and forging are to be carried out. This eventually consumes a considerable amount of time besides the yield being low [1].

To overcome this problem, technologists have come up with a new innovative technique called spray forming. The anonyms of it are spray casting or spray processing or spray deposition. Spray forming is basically a rapid solidification process wherein liquid metal is atomized in an inert gas atmosphere and sprayed in the form of fine droplets on to a substrate or a collector resulting in a near net shape preform. Thus spray forming produces components with fine grain structures and mechanical properties.

Genesis of spray forming

The concept of spray forming has come into existence in early 1970s. Prof. Singer pioneered the spray forming process at Swansea University, Wales, in the early 1970s as the spray rolling process [2–8]. His work was confined to Al alloys. Later on spray forming was further developed and subsequently licensed by Osprey metals, Neath, Wales, in early 1980s and consequently spray forming is often referred to as the "Osprey process" [9–16]. Further in late 1980s liquid dynamic compaction (LDC) process which is similar to spray forming was developed by Lavernia and Grant [17–19]. It is worthwhile to point out here that LDC,

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Osprey process, and spray forming are the generic names of similar or related processes. The melt in LDC was atomized at a high-gas pressure to generate the maximum yield of small size droplets in the spray. The cooling rate of a large fraction of droplets was well with in the rapid solidification regime [1]. Further developments in spray forming of Al alloys and its composites have been explained in detail in the following sections of this article.

Basics of spray forming technology

Spray forming being an emerging technology consists of a very few processing steps than the other emerging technologies like powder metallurgy. This process can be applied to a variety of ferrous and non-ferrous alloys and composites.

Details of spray forming equipment

The schematic diagram of a spray forming set up is as shown in Fig. 1 and the basic parts of it are a metal melting unit or a furnace, a gas atomizing unit, and a preform unit. A metal melting unit is basically a furnace used for melting alloys ranging from aluminum to steel and cast iron. It is fitted with a nozzle through which metal will be sprayed.

Inert gas is used for atomization. Generally nitrogen gas is used. This inert gas is passed through a convergent-divergent nozzle at the required pressure which is concentric to the nozzle of the furnace. This inert gas atomizes the liquid metal into fine droplets of liquid and this will be sprayed on to a substrate or a collector. The types of atomizers used are Free fall type, Confined type, and Ultrasonic type [1]. The preform unit consists of a substrate or a collector on which the atomized liquid droplets will be sprayed. The substrate can be held either horizontally or inclined and it can be either stationary or rotary type.

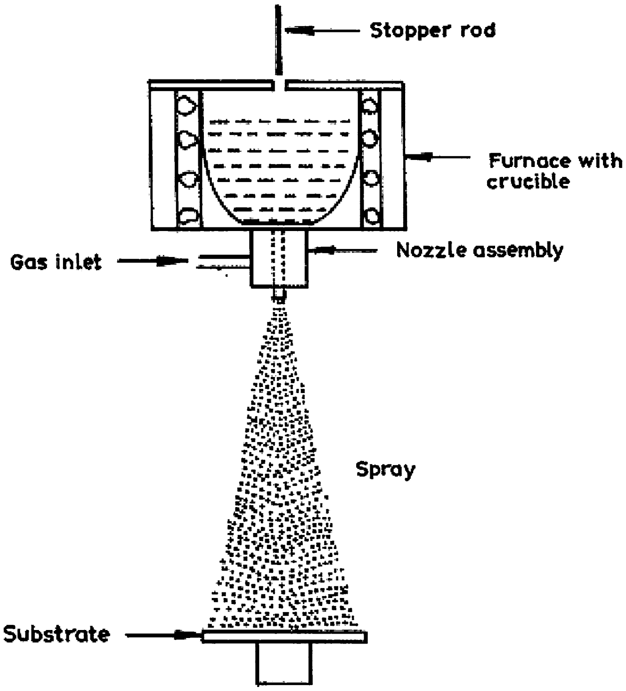


Fig. 1 A schematic diagram of spray forming set-up

Process parameters in spray forming process

The various process parameters in a spray forming process are as follows: melt to gas ratio, flow rate of molten metal, atomizing gas pressure, distance between the nozzle and the substrate and the orientation of the substrate. These parameters play a vital role in refining the microstructure of the preform and thereby enhance the mechanical and wear properties. These independent process parameters can be directly controlled during the process and affect a number of dependent process parameters like the state of spray at deposition and the state of the deposition surface. Therefore, these process parameters should be controlled to produce the optimum mixture of liquid and solid droplets that are essential for producing a quality preform [20–22].

Merits, demerits, and applications of spray forming

The various benefits that result from spray forming are: a near net shape preform, few processing steps, shorter manufacturing time, fine microstructure (uniform distribution of fine grains, no macroscopic segregation of alloying elements, and a low oxide content), better mechanical properties, better wear properties, composites can be produced, different shapes like billets, tubes, strips, and discs can be produced (Fig. 2), a wide variety of materials can be applied ranging from non-ferrous to ferrous metals and alloys and it is a cost-effective process [23–43].

The various demerits of spray forming are: spray formed preforms contain some porosity, material losses arise from over spray of droplets which do not impact on the substrate and bounce off of impacting droplets from the substrate surface, machining losses from out of specification preforms, and efficiency of spray forming process is low [2, 44, 45].

The spray-formed alloys and composites find a wide range of applications in automotive, aerospace, electronic packaging, and electrical industries. Also these are used as bearing materials and tribo-components for tribological applications [46–65].

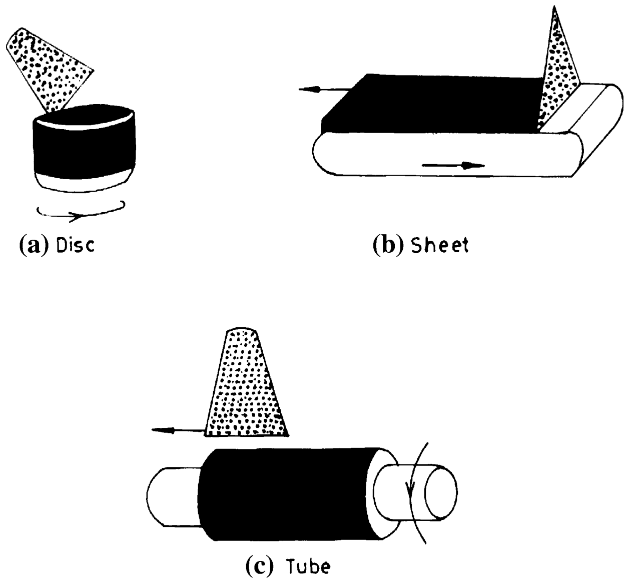


Fig. 2 Illustration of the near net shape production by spray forming [1]

A brief review of work done on spray forming of aluminum alloys and its composites

Research is going on, on various types of Al alloys and its composites. The alloys range from non-ferrous to ferrous alloys, that is, aluminum alloys to steel and cast iron alloys. In this article an overview of work that has been carried out on Al alloys and its composites in the past two decades has been summarized.

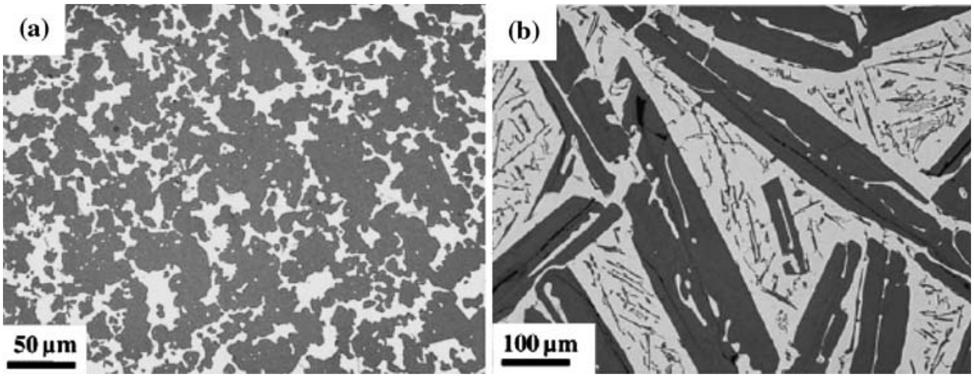
Spray forming of Al–Si alloys

Aluminum–silicon alloys find wide range of applications in automotive and aerospace industries. These alloys possess high strength to weight ratio, high wear resistance, and low coefficient of thermal expansion. These alloys show improved strength and wear properties as the silicon content is increased above eutectic composition. The work that has been carried out on these alloys has been summarized as follows. Researchers [66–68] have worked on Al–Si hypereutectic binary alloys. They have considered the effect of Si coarsening of these alloys and the effect of process parameters on the microstructural, mechanical, and wear properties of these alloys. Figure 3 depicts the as-sprayed and as-cast microstructures of one such hypereutectic alloy [66]. Srivastava et al. [69–71] have considered hypo and hypereutectic Al–Si binary alloys for their investigation and studied the microstructural characteristics (Fig. 4), mechanical properties (Table 1), and wear characteristics of these alloys. The hypoeutectic alloy showed a spherical morphology and the hypereutectic alloy showed a fine particulate morphology in their microstructures. Their investigation revealed that the microstructures consist of equiaxed Si grains with an average size of 5–7 μm in the Al matrix. Also the microstructures, mechanical and wear properties of as-sprayed alloys showed better results than their as-cast counterparts. The compositions of these hypo and hypereutectic alloys being used by various researchers under this category are as shown in Table 2.

Spray forming of Al–Si alloys with other non-ferrous alloying elements

Aluminum alloys with high silicon content with other non-ferrous elements like Cu, Mg, Ni, Cr, and Ti exhibit attractive properties such as lightness, high wear resistance, and low coefficient of thermal expansion. These properties can be effectively improved by further increasing the silicon content. However, this also leads to coarse silicon particles in the matrix, which reduces their mechanical properties and workability. Hence spray forming, a rapid solidification process, has been recognized as a novel process for manufacturing advanced materials that are potentially suitable for synthesizing aluminum alloys with

Fig. 3 Microstructures of (**a**) as-sprayed Si–30%Al alloy and (**b**) as-cast Si–30%Al alloy [66]



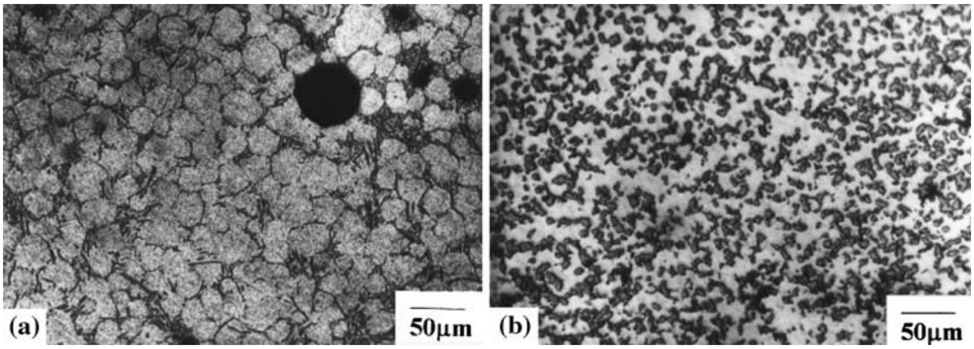


Fig. 4 Microstructures of as-sprayed alloys showing (**a**) spherical morphology of primary α-phase in Al–6.5%Si alloy and (**b**) particulate morphology of Si phase in Al–18%Si alloy [71]

Table 1 Mechanical properties of Al–Si alloys [71]

Alloy composition	Processing route	Tensile properties			Micro hardness (H_v)
		YS (MPa)	UTS (MPa)	EI (%)	
Al–6.5Si	AC	77.2	130.9	9.0	31.54
Al–6.5Si	SD + Ext.	75.5	132	34.3	39.35
Al–18Si	AC + Ext.	97.5	129	6.7	41.10
Al–18Si	SD + Ext.	119.5	158	18.7	58.57

Note: AC, as-cast; AC + Ext., as-cast and hot extruded; SD + Ext., spray deposited and hot extruded; YS, yield strength; UTS, ultimate tensile strength

Table 2 Compositions of hypo and hypereutectic Al–Si binary alloys

Alloy(s)	Reference
Si–30%Al	[66]
(i) Al–25%Si; (ii) Al–35%Si; (iii) Al–45%Si	[67]
(i) Al–6.5%Si; (ii) Al–18%Si	[69–71]
Al–25%Si	[68]

high silicon content [18]. The work that has been carried out on these alloys has been summarized as follows. Chiang and Tsao [67] have compared the microstructures (Fig. 5) and mechanical properties (Tables 3 and 4) of spray-formed hypereutectic alloys with that of squeeze cast alloys. The microstructure in spray-formed alloy is more uniform and found better than squeeze cast alloy. Hogg and Atkinson [72] have worked on a hypereutectic alloy whose composition is as shown in Table 5 and studied the microstructure of the alloy in a semi solid state. Anand et al. [78] have also worked on a hypereutectic alloy and found that the microstructure (Fig. 6) and mechanical properties of spray casting are better than the conventional casting. Researchers [73–77] have worked on hypoeutectic alloys. In their study they have investigated the microstructures of atomized powders, spray deposited preforms, and wear characteristics of these alloys. The compositions of the alloys used by various researchers under this category are as shown in Table 5.

Spray forming of Al–Si alloys with other non-ferrous and ferrous alloying elements

The stringent requirements of automotive and aerospace industries have prompted design of newer materials with high strength to weight ratio, low coefficient of thermal expansion, and high wear and corrosion resistance. Al–Si alloys containing other transition metals, particularly in hypereutectic composition regime, have created interest in the recent years due to their prerequisite properties. However, conventional techniques of processing of these materials lead to coarse and segregated microstructures with long plates of intermetallic transition metal compounds that give rise to inferior properties. This has led to the development of these materials through a rapid solidification technique called spray forming [23]. The work that has been carried out on these alloys has been summarized as follows. Researchers [79, 80] have considered hypereutectic alloys for their investigation. They have compared the microstructures of spray-formed alloys with that of their as-cast counterparts and found that the size of Si particles is 3–10 μm in spray-formed alloys and 90–150 μm in case of as-cast alloys (Figs. 7 and 8). Baiqing et al. [81] have found the influence of G/M ratio in spray forming process on size of primary Si phase in the hypereutectic alloy. With the increase of G/M ratio, the average of primary Si phase was reduced. Yang et al. [82] have worked on a hypereutectic alloy and studied the effect of Mn on the microstructure of the alloy. Researchers

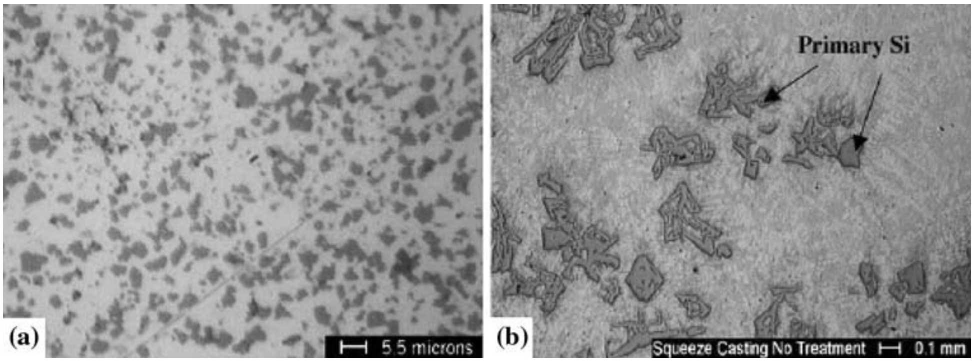


Fig. 5 Microstructures of (**a**) as-sprayed and (**b**) as-squeeze cast Al–25%Si–0.89%Cu–1%Ni–0.84%Mg alloy [67]

Table 3 Maximum micro hardness of spray-formed and squeeze cast alloys solution treated at various conditions [67]

Materials	Solutionizing temperature (K)	Time to reach the max. hardness (*h*)	Max. micro hardness (H_v)
Spray-formed alloy	773	3	85.7 ± 5.5
	788	3	106.8 ± 5.3
	803	2	106.7 ± 2.6
Squeeze cast alloy	773	4	75.0 ± 2.7
	788	2	88.2 ± 2.3
	803	1	87.8 ± 2.5

Table 4 Tensile properties of extruded spray-formed alloys at various heat treatment conditions [67]

Conditions	Elongation (%)	0.2% offset yield strength (MPa)	Ultimate tensile strength (MPa)	Fracture strength (MPa)
(1) As-extruded	7.2	108.9	262.9	258.2
(2) As-extruded + solutionizing[a]	4.3	199.9	342.7	339.5
(3) As-extruded + solutionizing[a] + peak aging[b]	3.4	235.3	366.0	336.9

[a] Solutionizing: 788 K, 3 h

[b] Peak aging: 473 K, 10 h

Table 5 Compositions of Al–Si alloys with other non-ferrous alloying elements

Alloy(s)	Reference
Al–25%Si–0.89%Cu–1%Ni–0.84%Mg	[67]
Al–30%Si–5%Cu–2%Mg	[72]
(i) Al–10%Si–3.5%Cu; (ii) Al–10%Si–20%Pb–3.5%Cu	[73]
75%Al–10%Mn–5%Cr–10%Si	[74]
Al–7%Si–0.3%Mg	[75]
(i) Fine grained: Al–(4–4.9%)Cu–(0.27–0.38%) Mg–(0.33–0.37%)Ag–(0.01–0.36%) Ti–(0.16–0.37)Zr–(0.21–0.27%)Mn	[76]
(ii) Coarse grained: Al–(4.7–4.9%)Cu–(0.27–0.41%) Mg–(0.36–0.40%)Ag–(0.32–0.33%)Ti–(0.09–0.13) Zr–(0.20–0.24%)Mn with Fe ≤ 0.05%, Si ≤ 0.3%	
6061 Al alloy (Al–Mg–Si)	[77]
Al–17%Si–4.5%Cu–0.6%Mg (A390 alloy)	[78]

[83–85] have worked on hypoeutectic alloys and compared the microstructures (Fig. 9), mechanical properties (Table 6), and wear characteristics of spray-formed alloys with that of as-cast alloys and found that spray-formed alloys are better than as-cast alloys. Prasad et al. [86] have worked on both hypo and hypereutectic alloys and investigated the microstructure, mechanical, and wear properties. Kalkanli et al. [87] have developed a 1D mathematical model by finite difference method for a Fe-based Al–Si alloy. The compositions of the alloys used under this category are as shown in Table 7.

Spray forming of Al–Si composites

Composite materials have become an attractive alternative to the traditional non-reinforced monolithic alloys. A large number of composite materials have metallic matrices reinforced with high strength, high modulus, and often brittle ceramic particles. There are various techniques available for processing the composites. An understanding of the factors that influence the strength and nature of wear is important for composites as these properties are sensitive

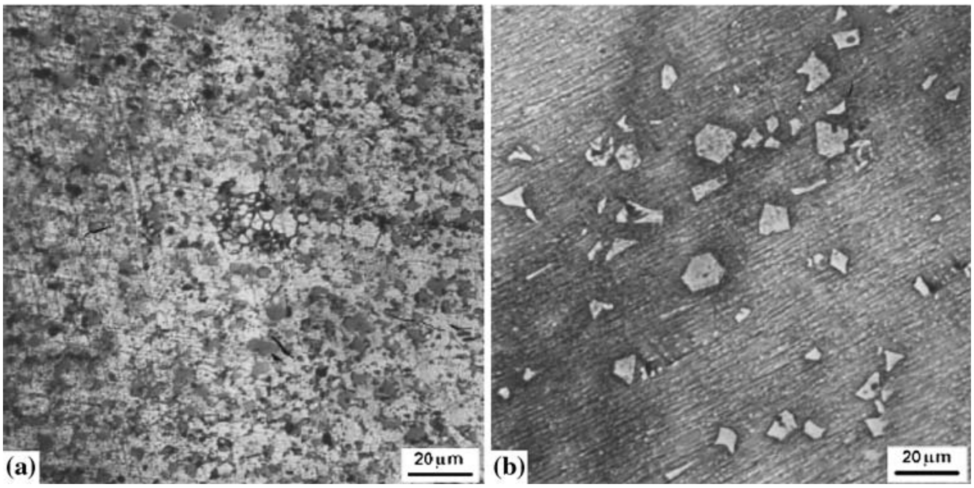


Fig. 6 Microstructures of (**a**) as-sprayed and (**b**) as-ingot cast A390 alloy [78]

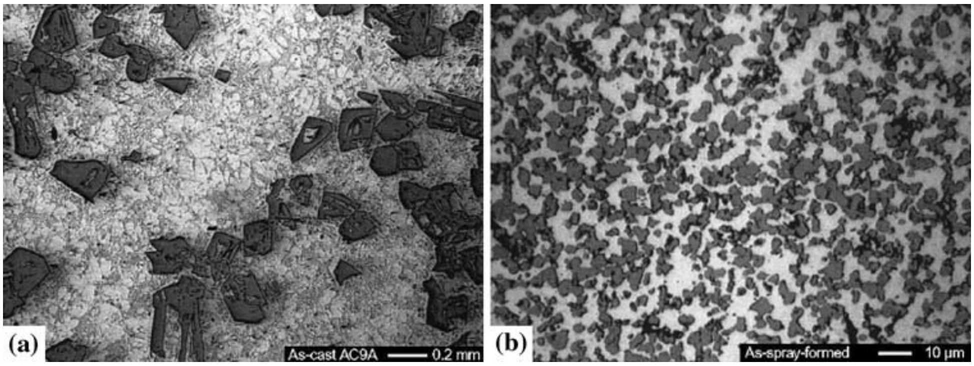


Fig. 7 Microstructures of (**a**) as-cast and (**b**) as-sprayed AC9A alloy [79]

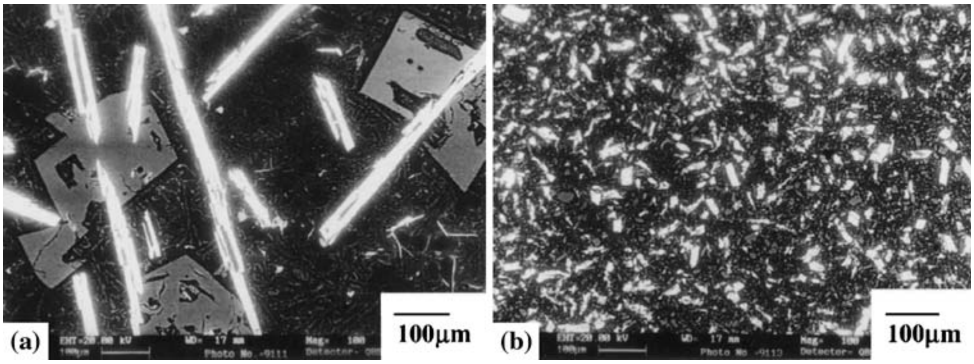


Fig. 8 Microstructures of (**a**) as-cast and (**b**) as-sprayed Al–18%Si–5%Fe–1.5%Cu alloy [83]

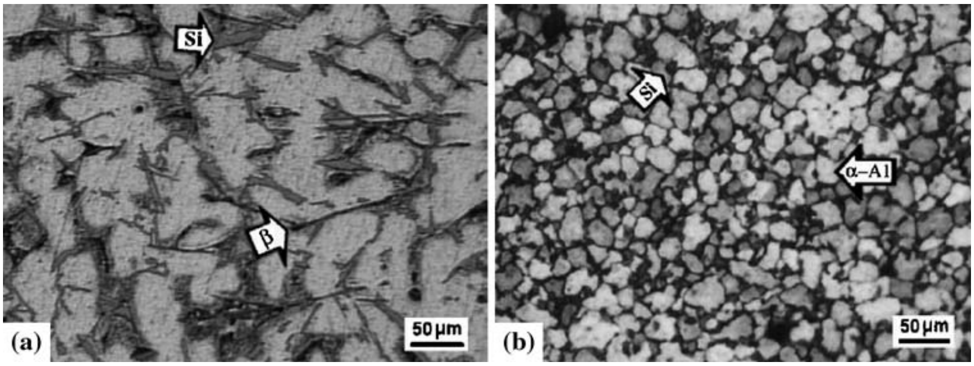


Fig. 9 Microstructures of (**a**) as-cast and (**b**) as-sprayed A380 alloy [80]

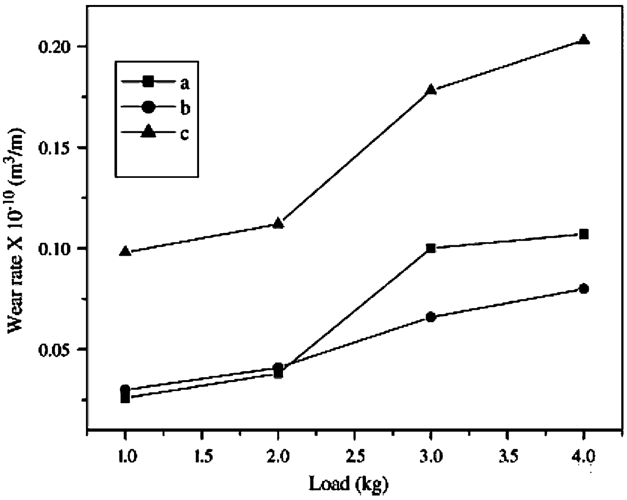


Fig. 10 Plot of wear rate versus load of (**a**) stir cast Al–2Mg–11TiO_2, (**b**) Spray formed Al–2Mg–11TiO_2, and (**c**) Al–2Mg alloy [92]

to the type of reinforcements and method of processing. One such method of processing is spray forming [27]. The work that has been carried out on Al–Si composites has been summarized as follows. Researchers [88–96] have worked on Al–Si composites. Most of them and in particular Chaudhury et al. have investigated the microstructures and wear characteristics of these spray-formed composites and found that they are better than stir cast composites (Fig. 10). Apart from this, aging response of composites has been compared with that of alloys and found that the composites have got superior response than the alloys [89, 93]. The compositions of the alloys used in this category are as shown in Table 8.

Table 6 Mechanical properties [83]

Processing route	Tensile properties			Porosity (%)
	YS (MPa)	UTS (MPa)	El (%)	
Sand casting	114	135	1.52	1
Spray forming	121	179	3.74	4

Note: YS, yield strength; UTS, ultimate tensile strength

Spray forming of Al with other non-ferrous alloying elements

In recent years Al–Li alloys have drawn a great deal of attention because of their attractive properties, that is, high stiffness, low density, etc., and their ability to offer weight savings up to 10–15%, that has got a greater value in the transportation and aerospace applications [97]. Al with other nonferrous alloying elements like Ti is currently being developed for applications as high as high temperature lightweight structural materials [98]. Liquid immiscible alloy like Al–Pb system is a potential material for advanced bearing applications due to their high thermal conductivity and low coefficient of friction [99].The work that has been carried out on Al with other nonferrous alloys has been summarized as follows. Gouthama et al. [99] have investigated the microstructures of atomized powders and spray-formed alloys as shown in Fig. 11. The wear rate of the alloy without Al is higher than that of Al alloy at low load and sliding velocity and is lower in severe regime at high load and sliding velocity (Fig. 12). Researchers [22, 97, 100, 101, 105–109, 111–114] have investigated the

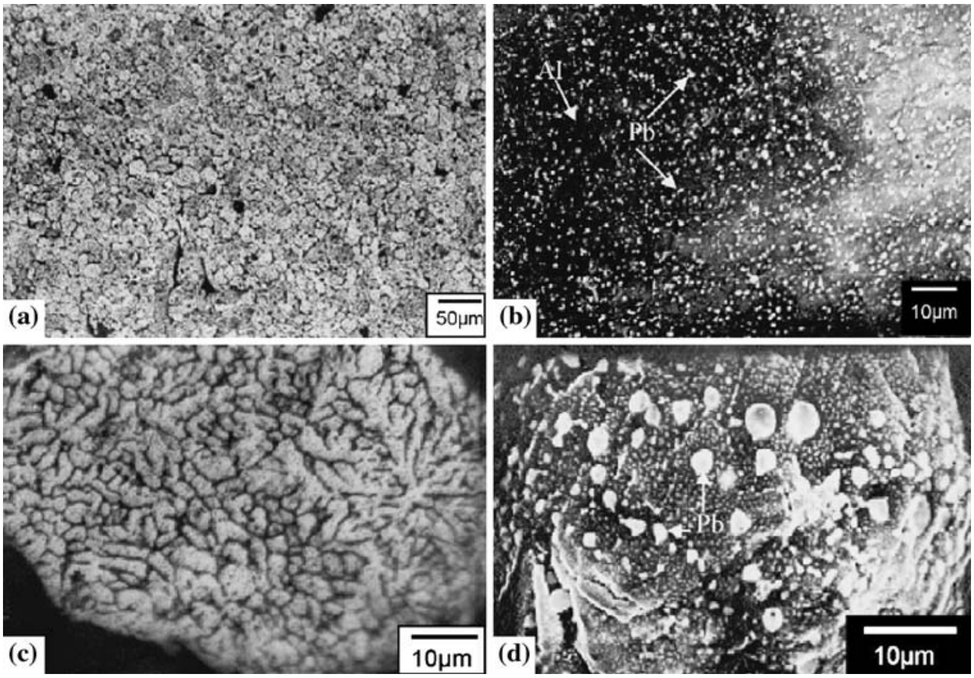


Fig. 11 Microstructures of (**a**) as-sprayed Cu–20Pb alloy, (**b**) as-sprayed Al–4Cu–20Pb alloy, (**c**) dendritic morphology of atomized powders of Cu–20Pb alloy, and (**d**) bimodal size distribution of Pb particles in atomized powders of Al–4Cu–20Pb alloy [99]

Table 7 Compositions of Al–Si alloys with non-ferrous and ferrous alloying elements

Alloy(s)	Reference
Al–22.2%Si–0.8%Cu–0.8%Ni–1%Mg–0.09%Zn–0.06%Ti–0.04%Mn–0.3%Fe (AC9A alloy)	[79]
Al–8.9%Si–3.2%Cu–0.9%Fe–0.8%Zn	[83]
Al–Fe–V–Si	[87]
Al–(19–20%)Si–(2–5%)Fe–(1–3%)Ni–(0.5–1.5%)Cu–(0.5–1.5%)Mg	[81]
(i) Al–11.47%Si–15%Pb–0.37%Fe–0.19%Cu–0.18%Mg–0.14%Mn	[84]
(ii) Al–8.05%Si–10%Pb–0.24%Fe–0.18%Cu–0.14%Mg–0.12%Mn	
Al–18%Si–5%Fe–1.5%Cu	[80]
Al–20%Si–5%Fe–3%Cu–1%Mg	[82]
Al–6.99%Si–0.08%Fe–0.01%Cu–0.34%Mg–0.11%Ti–0.01%Mn–0.01%Ni–0.01%Zn–0.001%Na–0.001%Ca	[85]
(i) Al–11.7%Si–1.02%Cu–1.5%Ni–1.08%Mg–0.70%Fe–0.80%Mn	[86]
(ii) Al–23.25%Si–0.80%Cu–1.10%Ni–1.21%Mg–0.71%Fe–0.61%Mn	

Table 8 Compositions of Al–Si composites

Alloy(s)/Composite(s)	Reference
(i) Al–4.5Cu–10Al_2O_3; (ii) Al–4.5Cu–10Al_2O_3–10Pb	[88]
(i) Al–9Zn–1.3Cu–0.3Mn–0.22Cr alloy	[89]
(ii) Al–8Zn–1.6Cu–4Mn–0.04Ag alloy	
(iii) Al–9Zn–1.1Cu–0.3Mn–0.22Cr+SiC_p composite	
(iv) Al–8Zn–1.6Cu–4Mn–0.04Ag+SiC_p composite	
Al–SiC_p composite	[90, 91, 93]
Al–2Mg–11TiO_2 composite	[92]
TiC/Al and TiC/Al–20%Si–5%Fe–3%Cu–1%Mg composites, TiC/Al–20%Si–5%Fe composite	[94]
6066Al/SiCp composite	[96]

Table 9 Compositions of Al alloys with other non-ferrous alloying elements

Alloy(s)	Reference
Al–4Cu–20Pb and Cu–20Pb	[99]
Al–Cu–Mg–Ti	[100]
γ–Ti–48.9%Al	[98]
Al–Zn–Mg–Cu	[22]
67Al–8Mn–24Ti–1Nb	[101]
Al–4.5%Cu	[102]
Al–12%Zn–2%Mg–2%Cu	[103]
Al–Y–Ni–Co	[104]
(i) Ti–48.9Al; (ii)Ti–47Al–4 (Nb,Mn,Cr,Si,B) [γ-TAB]	[105]
Al–6Cu–Mn	[106]
γ–Ti–48.9%Al	[107]
Al–3.8%Li–1.5%Cu–1%Mg–0.4%Ge–0.2%Zr	[108]
Al–2.5%Li–2%Cu–1%Mg–0.15%Zr	[97]
Al–Cu–Mg–Ag	[109]
2024 Al alloy (Al–Cu)	[110]
(i) Al–40%Zn–0.5%(Cu,Mg,Mn)	[111]
(ii) Al–60%Zn–0.5%(Cu,Mg,Mn)	
(iii) Al–70%Zn–0.5%(Cu,Mg,Mn)	
(iv) Al–78%Zn–0.5%(Cu,Mg,Mn)	
(i) Ni–21.8%Al–0.09%B–0.3%Zr	[112]
(ii) Ni–16.3%Al–0.03%B–8.1%Cr–1.7%Mo–0.5%Zr	
Ti–48Al–2Mn–2Nb	[113]
Al–4.5Cu–10Pb	[114]

microstructures (Figs. 13 and 14), mechanical properties (Tables 10–12), and wear characteristics (Fig. 15) of the alloys under this category whose compositions are as mentioned in Table 9 and compared them with their as-cast counterparts and found that the spray-formed alloys are better than the as-cast alloys. Staron et al. [98] have worked on an Al alloy. The texture of the spray-formed alloy in the as-sprayed state after isothermal forging and a subsequent stress relief heat treatment has been analyzed by means of neutron diffraction. The spray-formed deposit was found to have a very weak {111}-fiber texture with a maximum pole density of 1.2 multiples of random distribution. Shukla et al. [102] have developed a mathematical model of the spray deposition process, based on heat flow analysis during solidification of droplets as well as that of the spray deposit. A 1D heat transfer model, using a finite difference method, is used to calculate the temperature of deposit. The spray enthalpy on the deposition surface increases linearly with the melt superheat. Yang et al. [103] have investigated the low cyclic fatigue behavior of spray formed and hot rolled Al alloy whose composition is as mentioned in Table 9. It has been observed that the degree of cyclic strain hardening and the saturated cyclic stress amplitude increase with increasing applied total strain amplitudes. Golumbfskie et al. [104] have investigated the structure property relationship of a spray-formed Al alloy with two sets of processing conditions. Significant differences in tensile strength, yield strength, and high temperature ductility were observed w.r.t. the microstructural changes. Fracture toughness values were determined for both sets of specimens with a volume fraction of approximately 75%. It is believed that the specimens failed during fracture toughness testing by the mechanism of cleavage as observed in the Al_3Y intermetallic particles. Cai et al. [110] have worked on 2024 Al alloy. Low-pressure spray forming technique was used to produce the alloy and observed a decreased porosity in the alloy. Microstructures are similar to those achieved with conventional spray forming. The compositions of the alloys used in this category are as shown in Table 9.

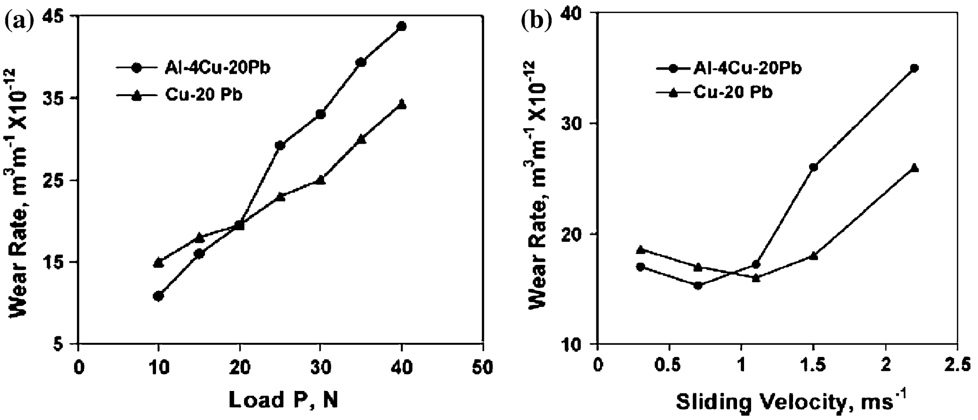


Fig. 12 (**a**) Variation in wear rate with applied load in spray-formed alloys. (**b**) Variation in wear rate with sliding velocity in spray-formed alloys [99]

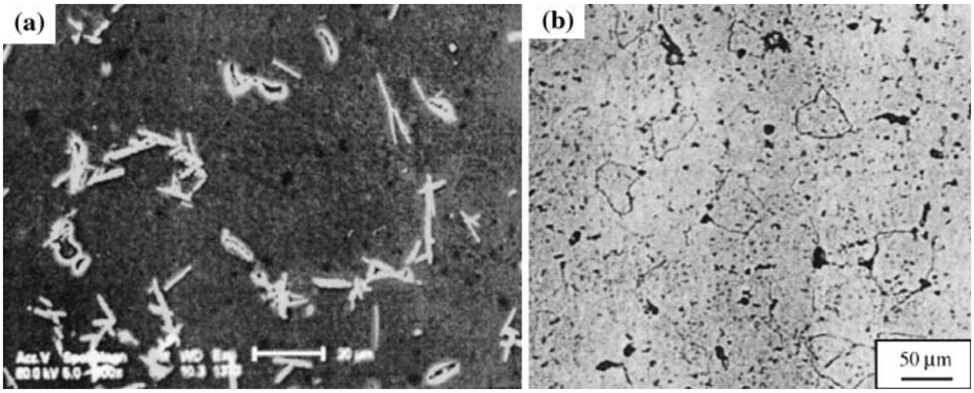


Fig. 13 Microstructures of (**a**) as-cast and (**b**) as-sprayed $Al_{67}Mn_8Ti_{24}Nb_1$ alloy [101]

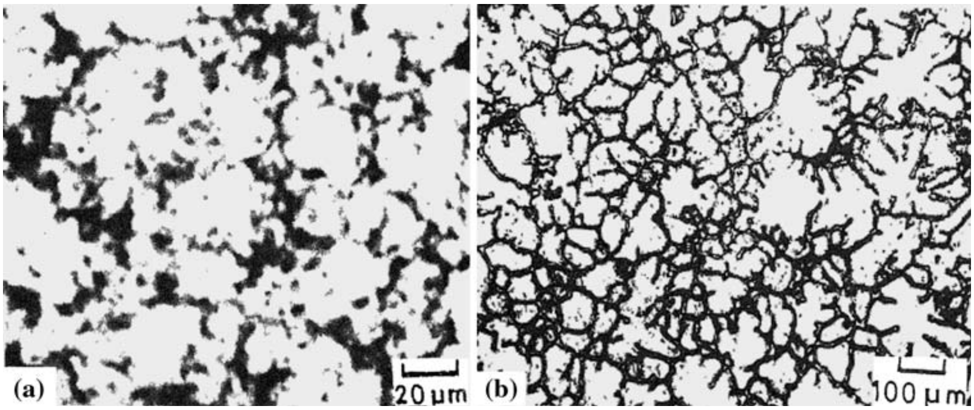


Fig. 14 Microstructures of (**a**) as-sprayed and (**b**) impeller mix as-cast Al–4.5Cu–10Pb alloy [114]

Table 10 Room temperature fracture toughness of $Al_{67}Mn_8Ti_{24}Nb_1$ alloys [101]

Fabrication processing	K_{IC} (MPa $m^{1/2}$)
As-cast	3.42
As-sprayed	3.10
As-milled powder consolidated	4.09

Spray forming of Al with ferrous alloying elements

Al–Fe alloys are suitable for high-temperature structural applications because of their good oxidation and hot corrosion resistance. They exhibit, however, limited room temperature ductility which has restricted their use. The ductility of these alloys may be improved by processing and compositional control [115]. The Al–Fe alloy system constitutes the basis of a family of commercially important elevated temperature Al alloys due to the very low diffusion rate of Fe in Al. The microstructure and phase stability of Al–Fe alloys are strongly influenced by the extent of under cooling during solidification as well as by concentration of Fe [115]. The work that has been carried out on Al with ferrous alloys has been summarized as follows. Juarez-Islas et al. [115] have studied the effect of

Table 11 Ambient temperature tensile properties and micro hardness of the aluminum alloy [109]

Material	YS (MPa)	UTS (MPa)	Elongation to failure (%)	Micro hardness	
				H_v	MPa
Homogenized ingot	525	559	12.0	77.2	757
Spray formed	505	549	17.0	126.8	1243

Note: YS, yield strength; UTS, ultimate tensile strength

Table 12 Mechanical properties of Al–4.5Cu–10Pb alloy [114]

Alloy composition (wt.%)	Processing method	UTS (MN m^{-2})	0.2% TPS (MN m^{-2})	0.2% CPS (MN m^{-2})	Hardness (BHN)	Elongation (%)
Al–4.5Cu	Impeller mix as-cast	196.8	141.2	174.3	57.0	10.8
Al–4.5Cu–10Pb	Impeller mix as-cast	152.6	96.1	141.2	48.1	12.1
Al–4.5Cu–10Pb	As-sprayed	160.0	117.2	151.6	54.2	11.7

Note: UTS, ultimate tensile stress; TPS, tensile proof stress; CPS, compressive proof stress

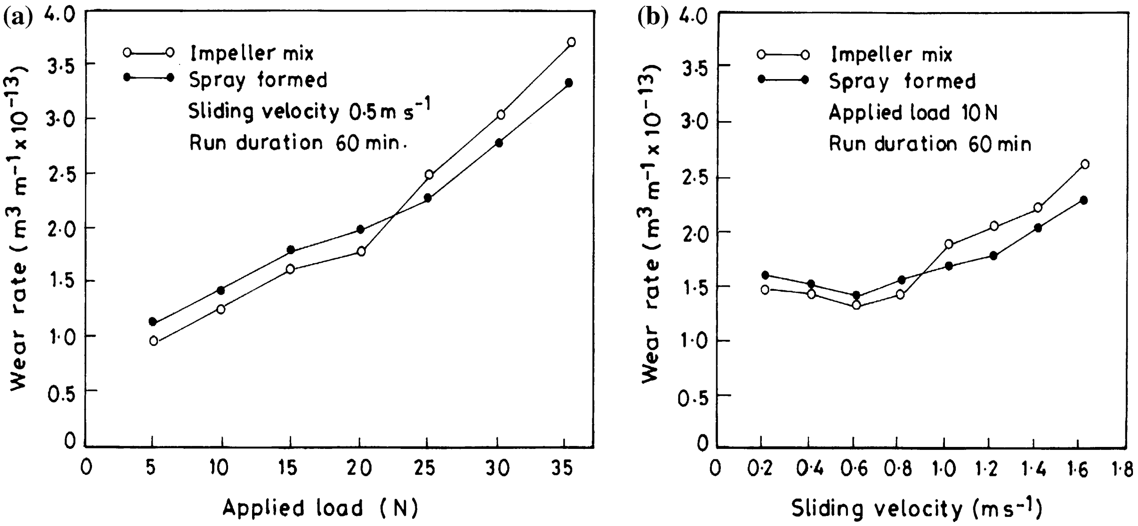


Fig. 15 (**a**) Variation in wear rate of Al–4.5Cu–10Pb alloy with applied load. (**b**) Effect of sliding velocity on wear rate of Al–4.5Cu–10Pb alloy [114]

Table 13 Compositions of Al with ferrous alloying elements

Alloy(s)	Reference
(i) Al–3Fe; (ii) Al–7Fe	[115]
Fe–12.5%Al–2.93%Ni–0.02%B	[116]

solidification history on the resultant microstructures in atomized Al–3Fe and Al–7Fe powders with particular emphasis on the relationships between droplet size, under cooling and phase stability. The atomized Al–Fe powders exhibit four microstructural features, that is, Al_3Fe phase, Al+Al_6Fe eutectic, α-Al dendrite, and a predendritic structure. The results of SEM analysis demonstrate that the content of Fe in the α-Al phase increases with decreasing powder particle size. Blackford et al. [116] have employed high-velocity oxy fuel spray forming for producing iron aluminide (Fe–12.5%Al–2.93%Ni–0.02%B) preform. The spray deposited layers exhibited some oxide and some porosity. This porosity was reduced by heat treatment. In heat treatment, the aluminide sprayed layer formed a nonprotective Fe_2O_3 oxide, rather than the usual Al_2O_3 that forms on binary alloy. The compositions of the alloys used in this category are as shown in Table 13.

Evolution of microstructure in Al–15%Si alloy

The microstructure of as-cast Al–15%Si alloy is as shown in Fig. 16a. From the figure it is clear that it contains dendrites with pro-eutectic Si and eutectic Si particles. The structure shows the presence of significant alloy segregation which is very much detrimental to the mechanical properties of the casting [117].

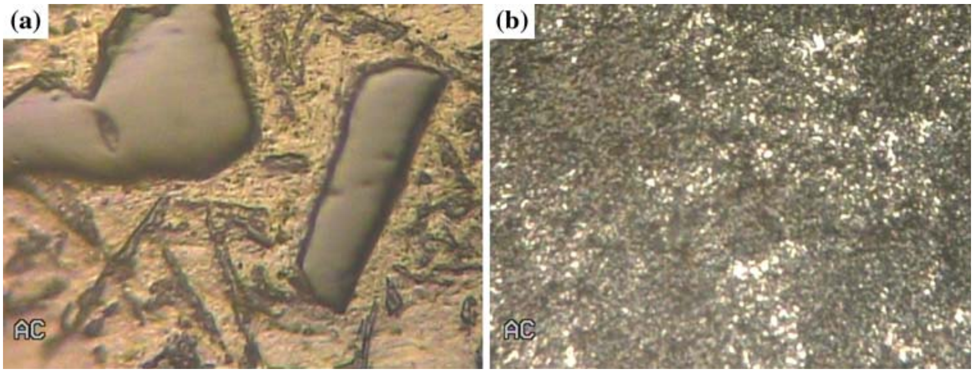


Fig. 16 Microstructures of (**a**) as-cast and (**b**) as-sprayed Al–15%Si alloy (magnification: 400×)

The problem of as-cast structure has been eliminated in as-sprayed structure. A variety of microstructures is observed in the spray deposit depending on the alloy composition, the nature of the spray, and the deposition condition of the droplets. In this section the microstructural observations made in the sample of Al–15%Si alloy are presented. The microstructure has invariably indicated equiaxed grains throughout the deposit. The Si particles have been distributed uniformly in Al matrix (Fig. 16b). Since the melt was atomized and spray deposited from a relatively high superheat to avoid liquid immiscibility in this system, most droplets arrived on the deposition surface in the liquid state. Impingement of the gas stream on the deposition surface provides rapid solidification of the liquid on the deposition surface.

The microstructural features generated in the preform are a combined consequence of the phenomenon which occurs in droplets during flight and their coalescence on the deposition surface. The spray contains droplets with different sizes and size distribution, velocities and thermal states on the point of impingement. When the rate of arrival of droplets in liquid or mushy state is such that the heat flux is balanced by the heat extraction rate, the individual droplets do not solidify before the arrival of subsequent droplets. As a result, the spray deposition condition gives rise to a liquid pool on the deposition surface. In this case the porosity of the deposit is greatly reduced and an equiaxed morphology is developed in the preform [1].

Singer and Evans [118] have suggested that equiaxed morphology is the consequence of large nucleation sites in the liquid arising from fine dendritic debris. The mechanical momentum transferred by high-velocity droplets on deposition surface creates considerable fluid flow and results in shearing of dendrites of the semi liquid or semi solid phase. In yet another investigation by Lavernia [119], the origin of fine equiaxed grain morphology in an Al alloy has been proposed to be a result of recrystallization in the preform during or after deposition. The ability of the spray forming process to generate refined equiaxed microstructure with low segregation is a major benefit in alloy development.

Conclusion

The work that has been carried out in the past two decades in the area of spray forming of Al alloys and its composites has been summarized in this article. The following conclusions have been drawn from the past research work.

1. Most of the research workers have focused their attention on the study of the microstructure of these alloys. A few of them have focused on the mechanical and wear characteristics of these alloys. Most of them have compared spray-formed alloys with that of chill cast alloys and found that spray forming provides better microstructure, mechanical and wear properties than chill casting.
2. In support of the above statement, an alloy of Al–15%Si has been spray formed and its microstructure has been compared with that of as-cast Al–15%Si alloy and found that the as-sprayed structure consists of equiaxed grains throughout the deposit with low segregation, which eventually provides better properties to the alloy.
3. Experimentation is going on, on various percentages of composition of Al–Si alloys and Al-Si with ferrous and nonferrous alloys and their composites. Optimization of various process parameters and percentages of composition has not been done so far. A wide scope is there to carryout research in this line toward optimization.
4. Optimized process parameters and percentages of composition of these alloys and their composites will result in enhanced properties, thus benefiting the aerospace and automotive industries.

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