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Processing techniques for particulate-reinforced metal aluminium matrix composites

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The critical need for high strength, lightweight and high stiffness materials has, in recent years, resurrected much interest in discontinuously reinforced powder metallurgy metal matrix composites. These hybrid materials have combined both standard wrought alloys of aluminium and a wide variety of discontinuous reinforcements such as particulates and whiskers of ceramic materials. Renewed interest in these materials as attractive candidates for use in the aerospace and transportation industry has resulted from an attractive and unique combination of physical and mechanical properties, and an ability to offer near isotropic properties coupled with the low cost of these materials when compared with existing monolithic materials. In this paper, the primary processing categories for discontinuously-reinforced metal-matrix composites are highlighted and the salient features of the various techniques in each category are discussed. The variables involved in each processing technique are examined, and the influence of alloy chemistry highlighted. Novel processing techniques for these materials such as the variable co-deposition method is presented as a means to process these novel engineering materials in order to improve their overall mechanical performance.

1. Introduction and background

The need for improved design procedures has resulted from an attempt to achieve significant improvement in structural efficiency, reliability and overall performance through reductions in either absolute weight or increases in strength-to-weight ratio. Reductions in material density or increases in stiffness, yield strength, ultimate tensile strength can be directly translated to reductions in structural weight. This led the aerospace industry to develop and examine new materials with combinations of low density, improved stiffness and high strength as attractive alternatives to existing high-strength aluminium alloys and titanium alloys. In a typical commercial airliner every pound of material saved translates into savings of about 250 $ in fuel costs over the projected life of an aircraft, at present day fuel prices [1, 2]. Savings in fuel result in savings in weight which translates directly into substantial increase in payload capabilities. For example, a 10% reduction in alloy density which can be achieved through substitution of lightweight aluminium–lithium alloys for conventional 2XXX and 7XXX series aluminium alloys will result in a 10% reduction in structural weight [2, 3]. A 10% saving in aircraft structural weight increases the available reserve payload by 4% [4–6]. Alternatively, a 50% increase in elastic modulus, which can be achieved through substitution of a discontinuous silicon carbide-reinforced aluminium alloy for an unreinforced wrought aluminium alloy, will also result in about 10% saving in structural weight [7]. Recent research results have made it possible to envision combining these effects through the development of reinforced lightweight alloys [3, 8–10].

System trade-studies, such as the ones outlined above, have been the primary motivating factor resulting in the resurrection of much interest in developing and using metal-matrix composites. Metal-matrix composites, in general, consist of at least two components, one is the metal matrix and the second component is a reinforcement. In all cases the matrix is defined as a metal, but a pure metal is rarely used as the matrix, it is generally an alloy. The distinction of metal-matrix composites from other two- or more, phase alloys comes about from the processing of the composite. In the production of the composite, the matrix and the reinforcement, are mixed together. This is to distinguish a composite from a two-, or more, phase alloy, where the second phase forms as a particulate and a phase separation such as a eutectic or a eutectoid reaction occurs. The metal-matrix composites offer a spectrum of advantages over conventional and/or traditional resin-matrix composites, that are important for their selection and use as structural materials. A few such advantages include the combination of high strength, high elastic modulus, high toughness and impact resistance, low sensitivity to changes in temperature or thermal shock, high surface

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TABLE I Typical reinforcements used in metal matrix composites [22]

Fibre[a]	Diameter (μm)	Tensile strength (MPa)	Elastic modulus[b] (10^6 p.s.i.)	Use limit (°F)	(°C)	Est. $\$ \mathrm{kg}^{-1}$
Boron (C)	100–200	3500	400	1000	538	\$ 575
Carbon graphite pan (C)	7.0	2400–4820	227–390	>3000	1649	\$ 38–1000
Carbon graphite pitch (C)	5.1–12.7	2067	400–700	>3000	1649	\$ 5–2750
SIC monofilament	140	4134	400	1700	927	\$ 1760
SIC (W)	6.0	3341	500–800	1700	927	\$ 210
FP alumina (C)	20	1378	400	>3000	1649	\$ 440
Fiberfrax (DC)	2–5	1723	90	2100	1149	\$ 2
3M Nextel 312 (C)	10	1378	150	3000	1649	\$ 22
ICI Saffill (C)	3	2000	300	3000	1649	\$ 51

[a] C = continuous, W = whisker, DC = discontinuous.

[b] 10^3 p.s.i. $\simeq 6.89\ \mathrm{N\,mm^{-2}}$.

durability, low sensitivity to surface flaws, high electrical and thermal conductivity, minimum exposure to the potential problem of moisture absorption resulting in environmental degradation, and improved fabricability with conventional metal working equipment [11–20]. One of the first applications of metal-matrix composites was for the Space Shuttle. Lightweight, high stiffness struts made of continuous fibre boron–aluminium composite make up much of the framework of the Shuttle fuselage. The composite tubes, 243 in number, have different configurations and weigh about 330 lb (~149.68 kg). Use of the metal-matrix composite allowed smaller tube diameter to be used than would have been possible with conventional extruded aluminium. The composite has lower thermal conductivity, thereby reducing the amount of insulation required between the payload bay and the skin [21]. In recent years, the particulate-reinforced metal-matrix composites have emerged as attractive candidates for use in a spectrum of applications to include industrial, military and space-related.

The renewed interest in metal-matrix composites has been aided by the development of reinforcement material which provides either improved properties or reduced cost when compared with existing monolithic materials. Metal-matrix composite reinforcements can be generally divided into five major categories: (a) continuous fibres, (b) discontinuous fibres, (c) whiskers, (d) wires, and (e) particulates (including platelets). With the exception of wires, which are metals, reinforcements are generally ceramics. Typically these ceramics are oxides, carbides and nitrides which are used because of their excellent combinations of specific strength and stiffness at both ambient temperature and at elevated temperatures. The typical reinforcements used in metal-matrix composites are listed in Table I. Silicon carbide, boron carbide and aluminium oxide are the key particulate reinforcements and can be obtained in varying levels of purity and size distribution. Silicon carbide particulates are also produced as a by-product of the processes used to make whiskers of these materials. A recent advance in this arena is the production of single-crystal silicon carbide platelets which have the potential in achieving near isotropic properties in metal-matrix composites [22].

TABLE II Typical matrix alloys [22]

- Aluminium
- Titanium
- Magnesium
- Copper
- Bronze
- Nickel
- Lead
- Silver
- Superalloys (nickel- and iron-based)
- Niobium (columbium)
- Intermetallics
  - Nickel aluminides
  - Titanium aluminides

Over the years, several metallic systems have been considered for use as a matrix material for metal matrix composites (Table II). The most important have been the non-ferrous lightweight materials for structural use such as aluminium, titanium and magnesium because specific properties of these materials can be enhanced to replace heavier monolithic materials. Aluminium is the most attractive non-ferrous matrix material used particularly in the aerospace and transportation industries where weight of structural components is critical. Development of newer generation aircraft has placed stringent requirements on performance of aluminium alloys because the temperatures to which they are exposed is steadily increasing. An approach used to attain better elevated temperature properties in aluminium has come from the development of rapid solidification rate (RSR) alloys in which metastable precipitates formed by rapid cooling rate strengthen the alloy by inhibiting slip. An alternative approach used to obtain better elevated temperature properties is to utilize composite materials technology, and reinforce an aluminium matrix with fibres or particulates. The various composite systems currently being explored with some degree of commercial interest are listed in Table III.

TABLE III Metal matrix composite systems being explored with some degree of commercial intent [22]

Reinforcement	Matrices
Boron, fibre (including coated)	Aluminium, titanium
Graphite fibre	Aluminium, magnesium, copper
Alumina fibre	Aluminium, magnesium
Silicon carbide fibre	Aluminium, titanium
Alumina–silica fibre	Aluminium
Silicon carbide whisker	Aluminium, magnesium
Silicon carbide particulate	Aluminium, magnesium
Boron carbide particulate	Aluminium, magnesium

Early studies on metal-matrix composites addressed the development and behaviour of continuous fibre-reinforced hybrid materials based on aluminium and titanium matrices [23, 24]. Unfortunately, despite encouraging results, extensive industrial application of these composite materials was hindered by: (i) exorbitant manufacturing costs associated with the high cost of reinforcement material {that is, \$660 kg^{-1} for boron fibres}, and (ii) the high labour-intensive manufacturing process. Consequently, effective utilization of these materials was restricted to military and other highly specialized applications. The family of discontinuously reinforced metal-matrix composites include those with particulates, whiskers and platelets. Particulate-reinforced composites are intended herein to include those composites having more than 10 vol % hard reinforcing dispersed phase and do not include the class of dispersion hardened metals, which have a considerably lower volume fraction of dispersoid. Besides the diameter of the particles, the interparticle spacings are much greater in the composite, normally greater than 1.0 μm compared to the 0.01–0.1 μm interparticle distances in dispersion hardened metals [25].

In recent years, particulate-reinforced metal-matrix composites have attracted considerable attention on account of [26] (a) availability of a spectrum of reinforcements at competitive costs, (b) successful development of manufacturing processes to produce metal-matrix composites with reproducible microstructures and properties, and (c) availability of standard and near standard metal working methods which can be utilized to form these materials. Furthermore, use of discontinuous reinforcements minimizes problems associated with fabrication of continuously reinforced metal-matrix composites such as fibre damage, microstructural heterogeneity, fibre mismatch and interfacial reactions. For applications subjected to severe loads or extreme thermal fluctuations such as in automotive components, discontinuously-reinforced metal-matrix composites have been shown to offer near isotropic properties with substantial improvements in strength and stiffness, relative to those available with monolithic materials [26–29]. However, the discontinuously-reinforced composite materials are not homogeneous and material properties are sensitive to properties of the constituent, interfacial properties and geometric shape of the three-dimensional reinforcement. Overall, strength of such particle-reinforced metal matrices depends on: (a) the diameter of the reinforcing particles, (b) the interparticle spacing, (c) the volume fraction of the reinforcement, and (d) condition at the matrix–reinforcement interface. Matrix properties, including the work hardening coefficient, which improves the effectiveness of the reinforcement constraint, are also important.

The objective of this review is to examine the various processing techniques that have been used for producing particulate-reinforced metal-matrix composites. In particular, the role of processing variables are examined in an attempt to obtain guiding information that will permit us to improve the mechanical performance of these materials.

2. Processing

Over the years a spectrum of processing techniques have evolved in an attempt to optimize the microstructure and mechanical properties of particulate-reinforced metal-matrix composites [21, 28–38]. The processing methods utilized to manufacture particulate-reinforced metal matrix composites can be grouped according to the temperature of the metallic matrix during processing. Accordingly, the processes can be classified into three categories: (1) liquid-phase processes, (2) solid-phase processes, and (3) two-phase (solid/liquid) processes. A review of the salient features of each of the above processes is provided in this section.

2.1. Liquid-phase processes

In liquid-phase processes, the ceramic particulates are incorporated into a molten metallic matrix using various proprietary techniques. This is followed by mixing and eventual casting of the resulting composite mixture into either shaped components or billets for further fabrication (Fig. 1). The process involves a careful selection of the ceramic reinforcement depending on the matrix alloy. In addition to compatibility with the matrix, the selection criteria for a ceramic reinforcement includes the following factors [25]: (a) elastic modulus, (b) tensile strength, (c) density, (d) melting temperature, (e) thermal stability, (f) size and shape of the reinforcing particle, (g) coefficient of thermal expansion, and (h) cost. The various possible discontinuous ceramic reinforcements and their properties are summarized in Table IV. Most ceramic reinforcement materials are not wetted by the molten alloy. Consequently, introduction and retention of the ceramic particulate necessitates addition of wetting agents to the melt, or coating the ceramic particulates prior to mixing.

2.1.1. Liquid metal/ceramic particulate mixing

Several approaches have been utilized to introduce ceramic particles into an alloy melt [54]. These include:

(a) injection of powders entrained in an inert carrier gas into the melt using an injection gun;

(b) addition of ceramic particulates into the molten stream as it fills the mould;

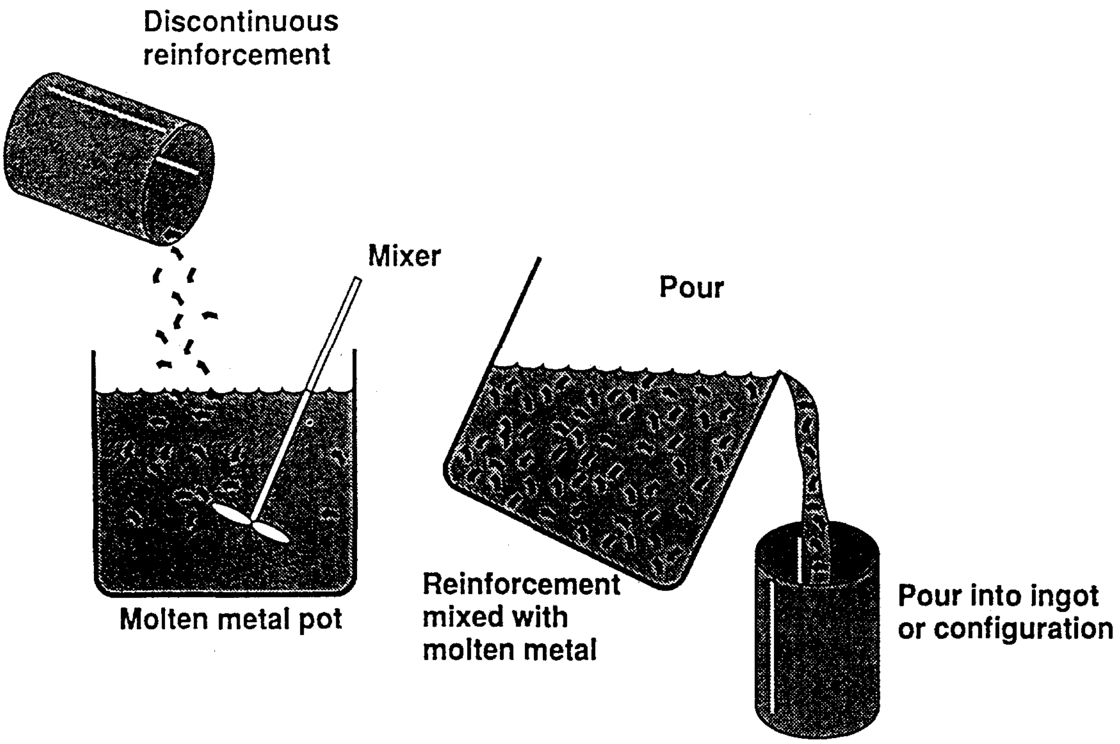

Figure 1 Flow chart highlighting a typical liquid blending fabrication technique [22].

TABLE IV Properties of selected ceramic reinforcements [25, 39, 40]

Ceramic	Coefficient of expansion ($10^{-6}/°F^{-1}$)	Strength (MPa)	Elastic modulus (GPa)
BeO	4.1	24 (2000°F)	190 (2000°F)
MgO	6.45	41 (2000°F)	150 (2000°F)
ThO_2	5.3	190 (2000°F)	200 (2000°F)
UO_2	5.3	–	175 (2000°F)
ZrO_2	6.67	85 (2000°F)	130 (2000°F)
CeO_2	6.9	600 (75°F)	200 (75°F)
Al_2O_3	4.4	220 (2000°F)	380 (2000°F)
$TaSi_2$	6.0	–	340 (2300°F)
$MoSi_2$	4.85	280 (2000°F)	280 (2300°F)
WSi_2	5.0	–	250 (2000°F)
TiB_2	4.6	–	410 (2000°F)
ZrB_2	4.5	–	503 (75°F)
TiC	4.22	55 (2000°F)	270 (75°F)
ZrC	3.7	90 (2000°F)	360 (75°F)
HfC	3.7	–	320 (75°F)
VC	3.98	–	430 (75°F)
NbC	3.8	–	340 (75°F)
TaC	3.59	–	360 (75°F)
Mo_2C	3.23	–	230 (75°F)
WC	2.83	–	670 (75°F)
B_4C	3.38	2800 (75°F)	450 (75°F)
SiC	3.00	–	325 (2000°F)
AlN	2.69	2100 (75°F)	310 (2000°F)

(c) addition of particulates into the molten metal through a vortex introduced by mechanical agitation;

(d) addition of small briquettes into the melt followed by immediate stirring (the briquettes are made from co-pressed aggregates of the base alloy powder and the solid particulates);

(e) forcing the particulates into the melt through the use of reciprocating rods;

(f) dispersion of the fine particulates in the melt by centrifugal action;

(g) injection of particulates into the melt while the melt is continuously irradiated with ultrasound; and

(h) zero-gravity processing. The zero gravity approach involves utilizing the synergism of ultra-high vacuum and elevated temperatures for prolonged periods of time.

In all of the above processes, a strong bond between the metal-matrix and the reinforcement is achieved by utilizing high processing temperature (e.g. more $T > 900\,°C$ for the aluminium/aluminium oxide system), and alloying the matrix with an element which interacts with the reinforcement to produce a new phase, and thereby, effect "wetting" between the matrix and the ceramic (e.g. silicon carbide in the aluminium–lithium system). This reaction must be constrained so as to be adequate enough to wet the reinforcement to promote bonding, without causing reinforcement degradation during composite fabrication and/or utilization. Agitation during processing is essential to disrupt the formation of contamination films and absorbed layers. This facilitates interfacial bonding.

The liquid-phase processes have reached an advanced stage of development and fine ceramic particulates of silicon carbide or aluminium oxide are added to a variety of aluminium alloy matrices [28–31]. However, despite the encouraging results provided with liquid-phase processes, several difficulties exist. These include (i) an agglomeration of the ceramic particles during mechanical agitation, (ii) settling of the ceramic particulates, (iii) segregation of the secondary phases in the metal matrix, (iv) extensive interfacial reactions, and (v) ceramic particulate fracture during mechanical agitation.

In recent years, the Dural process has arisen as the most advanced and ideal in terms of commercial development. The Dural process involves an incorporation of ceramic particulates into the metallic matrix through melt agitation. A summary of mechanical properties of various metal matrix composites produced by the Dural process are shown in Table V. The results summarized in this table suggest that it is possible to combine up to 20 vol % of either silicon carbide or aluminium oxide with various aluminium alloys in order to obtain metal-matrix composites with an attractive combination of properties.

2.1.2. Melt infiltration

In the melt infiltration process, a molten alloy is introduced into a porous ceramic preform utilizing either an inert gas or a mechanical device such as a pressurizing medium. The pressure required to combine the matrix and reinforcement is a function of friction effects arising from viscosity of the molten matrix as it fills the ceramic preform. Wetting of the ceramic preform by the liquid alloy depends on several competing factors such as alloy composition, nature of ceramic preform, ceramic surface treatment, surface geometry, interfacial reactions, surrounding atmosphere, temperature and time [37, 38]. This approach has been studied extensively, and is currently being used commercially to fabricate the Toyota diesel piston, an aluminium/chopped alumina fibre composite material [41].

The primary drawbacks of melt infiltration process include reinforcement damage, compression of the preform, microstructural heterogeneity, coarse grain size, mutual contact between reinforcement fibres and/or particulates, and undesirable interfacial reactions [42].

2.1.3. Melt oxidation process

In melt oxidation processing (i.e. the Lanxide™ process), a ceramic preform, formed into the final product shape by a fabricating technique such as pressing, injection moulding or slip casting, is continuously infiltrated by a molten alloy as it undergoes reaction with a gas phase. Basically a chemical reaction is used to cause aluminium to infiltrate the ceramic preform. Alumina (Al_2O_3) and silicon carbide (SiC) in volumes of 55%–60% are used with aluminium alloy matrices to form near net shape parts. An aluminium alloy ingot containing 3–10 wt % magnesium is placed on top of a permeable mass of ceramic material, either alumina or silicon carbide. The alloy–ceramic assembly is heated in an atmosphere of nitrogen, at temperatures between 1475 and 1835 °C. Spontaneous infiltration takes place provided (a) the alloy contains magnesium, (b) the temperature is at least 1475 °C, and (c) the atmosphere is mostly nitrogen (Fig. 2) [43–45].

Because of the nitrogen atmosphere, aluminium nitride is formed within the microstructure. The amount depends inversely on the speed of the reaction, with more aluminium nitride forming at slower infiltration speeds. Infiltration speed is slower at lower temperatures and lower nitrogen content of the atmosphere. This is significant because an increase in the amount of aluminium nitride increases the stiffness of the composite and reduces the coefficient of thermal expansion (CTE). Therefore, stiffness and CTE can be tailored by controlling the process temperature and

TABLE V (a) Mechanical properties of Duralcan Al-MMC alloys [30]

Alloy[a]	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)	Modulus (GPa)	K_{IC} (MPa m$^{1/2}$)
6061–0% Al_2O_3	276	310	20.0	69	29.7
6061–10% Al_2O_3	297	338	7.6	81	24.1
6061–15% Al_2O_3	386	359	5.4	88	22.0
6061–20% Al_2O_3	359	379	2.1	99	21.5
2014–0% Al_2O_3	414	483	13.0	73	25.3
2014–10% Al_2O_3	483	517	3.3	84	18.0
2014–15% Al_2O_3	476	503	2.3	92	18.8
2014–20% Al_2O_3	483	503	0.9	101	–
A356–0% SiC	200	276	6.0	75	–
A356–10% SiC	283	303	0.6	81	–
A356–15% SiC	324	331	0.3	90	–
A356–20% SiC	331	352	0.4	97	–

[a] Solution treated to T6 condition.

(b) Physical properties of Duralcan A356-SiC

	0% SiC	15% SiC
Density (g cm^{-3})	2.68	2.76
Electrical conductivity (%IACS, at 22 °C, F temper)	37.50	27.60
Thermal conductivity (W m^{-1} °C^{-1}, T temper)	150.57	173.94

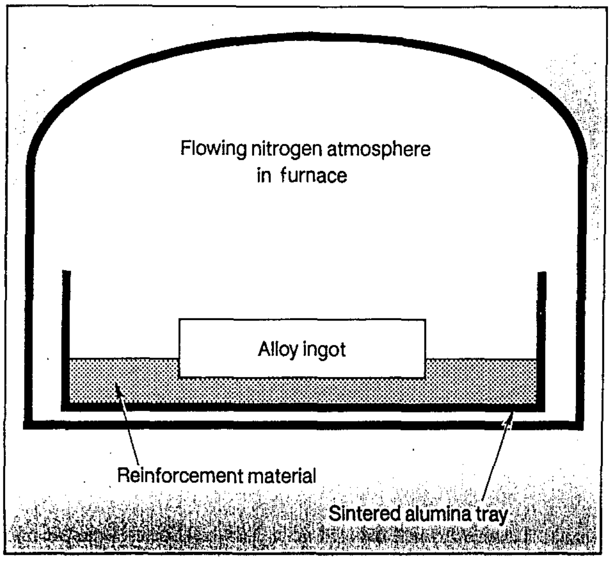

Figure 2 The Lanxide process which uses a pressureless infiltration technique to incorporate the matrix alloy into the ceramic preform. An aluminium alloy ingot is placed on the ceramic reinforcing material, then heated to 800–1000 °C in a flowing nitrogen atmosphere [43, 44].

the amount of nitrogen in the atmosphere. Also high-temperature oxidation of the molten alloy in the interstices of the ceramic preform produces a matrix material composed of a mixture of oxidation reaction products and unreacted metal alloy [44]. The primary advantage of this process is its ability to form complex, fully dense composite shapes. An attractive combination of mechanical properties have been reported for aluminium-based metal-matrix composites processed using this approach (Table VI [31]). A joint venture between Lanxide and Alcan resulted in the production of a commercial composite designated as Alcan CG893, an alumina/aluminium alloy matrix grown around silicon carbide filler. This product has demonstrated to exhibit an exceptional resistance to erosive wear [45].

2.2. Solid-phase processes

The fabrication of particulate-reinforced metal-matrix composites from blended elemental powders involves number of stages prior to final consolidation. The salient features of two of the processes, namely, powder metallurgy and high energy rate processing are described.

2.2.1. Powder metallurgy

Solid phase processes involve the blending of rapidly solidified powders with particulates, platelets or whiskers, through a series of steps as summarized in Fig. 3. The sequence of steps include: (i) sieving of the rapidly solidified particles, (ii) blending of the particles with the reinforcement phase(s), (iii) compressing the reinforcement and particle mixture to approximately 75% density, (iv) degassing and final consolidation by extrusion, forging, rolling or any other hot working method. This technology has been developed to various degrees of success by various commercial manufacturers, including Aluminum Company of America (ALCOA, Pittsburgh, PA), Ceracon Inc (Sacramento, CA), DWA Composites Specialties Inc (Chatsworth, CA), Naval Surface Weapons Center, White Oak Laboratory (Silver Spring, MD) and Advanced Composite Materials Corporation (Greer, SC). The ALCOA and Ceracon processes are shown schematically in Figs 4 and 5. The process sequence involved in the Ceracon process is succinctly summarized by a flow chart (Fig. 6).

A spectrum of silicon carbide particulate sizes and shapes are available as reinforcements. Typical α (hcp) and β (bcc) silicon carbide crystal structures have been examined as possible reinforcements [32]. Selection of an appropriate silicon carbide particulate size is determined by the ratio of appropriate size of silicon carbide to metal powder size [33–35]. Table VII

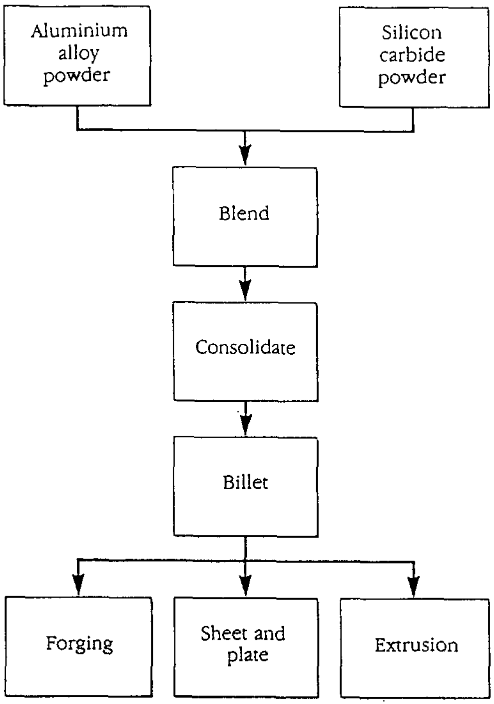

Figure 3 Flow chart showing key fabrication steps for a powder metallurgy metal-matrix composite.

TABLE VI Mechanical properties of some Lanxide™ composites [31]

Matrix/Reinforcement	Four-point test (MPa)	Toughness (MPa m$^{1/2}$)
Aluminium–Al_2O_3/Al_2O_3 particulates	500	9
Aluminium–Al_2O_3/SiC particulates	523	8.0
Aluminium–Al_2O_3/Nicalon™ fibres	997	29.0

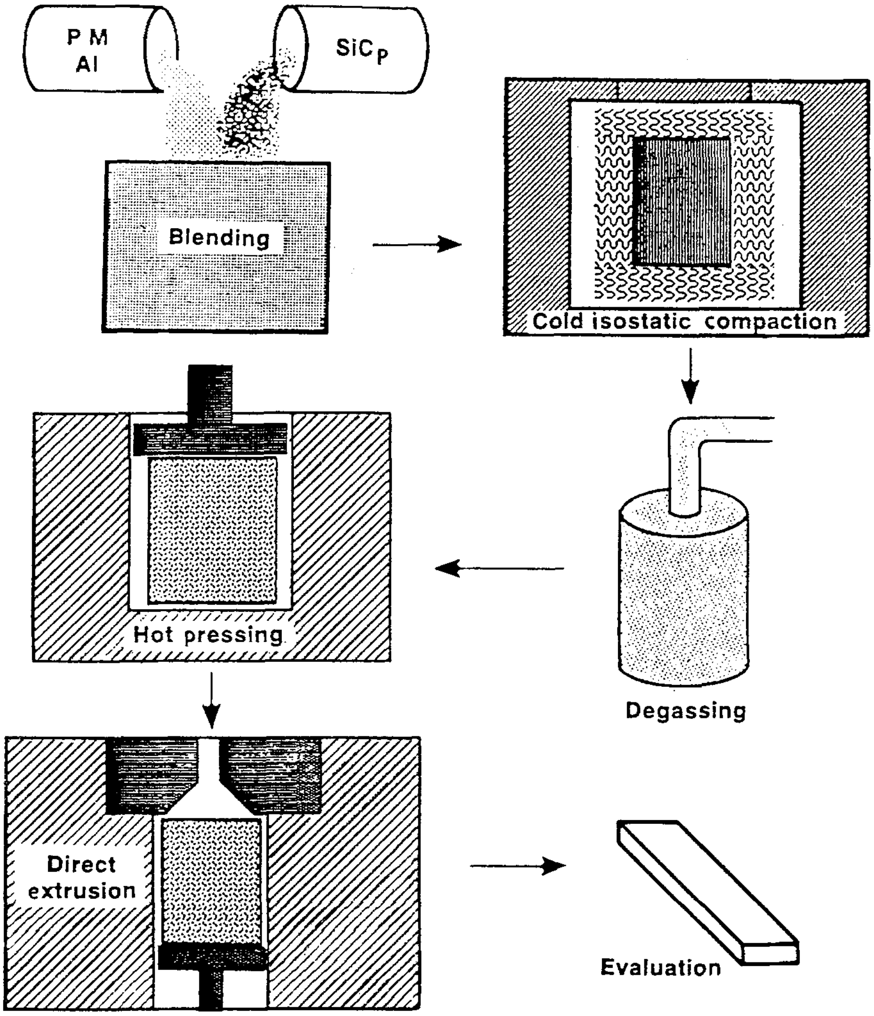

Figure 4 Schematic interpretation of the processing route for PM aluminium-silicon carbide particulate composites [35].

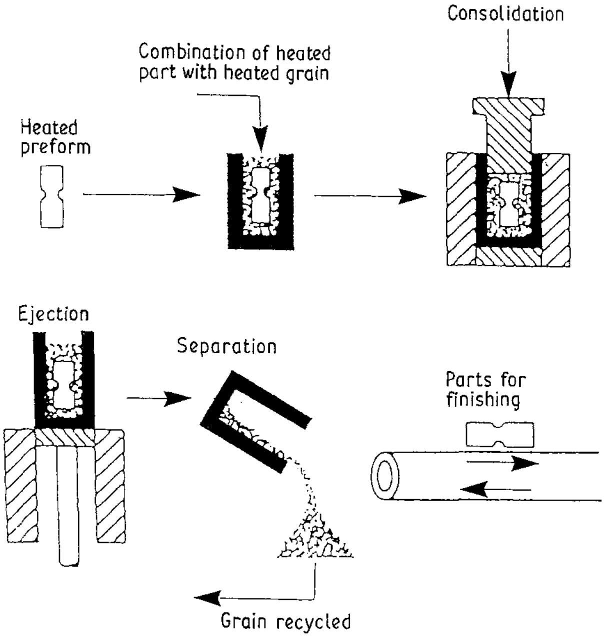

Figure 5 Schematic illustration of the Ceracon technique for fabricating PM metal matrix composites (from [46, 47]).

presents the chemical composition of a few aluminium alloys that have been or are being examined as possible matrix alloys. The most popular initial choices were the standard wrought compositions 2124 and 6061 [26]. These alloys were prepared as elemental or pre-alloyed air/helium inert gas atomized powder. Other matrix compositions that have been investigated include aluminium alloys 7090, 7091, Al–Fe–Ce and Al–Cu–Li–Mg. These alloys take the full benefit of rapid solidification.

In the powder metallurgy approach developed by ALCOA the reinforcement material is blended with rapidly solidified powders. The blend is then consolidated into billets by cold compaction, outgassed and hot isostatic or vacuum hot pressed (Fig. 7) to form starting products for subsequent fabrication. The cold compaction density is controlled in order to maintain open, interconnecting porosity. This is essential during the following stage of degassing or outgassing during the pressing operation. The process of outgassing normally involves removal of adsorbed and/or chemically combined water and other volatile species through the combined action of heat, vacuum and inert gas flushing. For silicon carbide-reinforced metal-matrix composites, the outgassing aids in removal of adsorbed water for both silicon carbide and aluminium and also any chemically bound water from the matrix material [25]. An advantage of this technique is an ability to use the improved properties of advanced rapidly solidified powder technology in the composite. Both technologies have the added advantage of offering near isotropic properties in the body.

In the Ceracon process, the final densification is achieved by hot pressing in a pressure transmitting medium (PTM) [46]. The mechanical properties of an extruded composite containing silicon carbide whiskers and particulates are shown in Table VIII [48]. The results reveal that the powder metallurgy processed aluminium/silicon carbide metal-matrix composites possess higher overall strength levels compared to equivalent material processed by the liquid-phase process, and also exhibit a slight improvement in tensile ductility. In terms of final microstructural refinement, the powder metallurgy approach is superior and is preferred in view of the rapid solidification experienced by the powders. This permits the development of novel matrix materials outside the compositional limits dictated by equilibrium thermodynamics in conventional solidification processes [49–51].

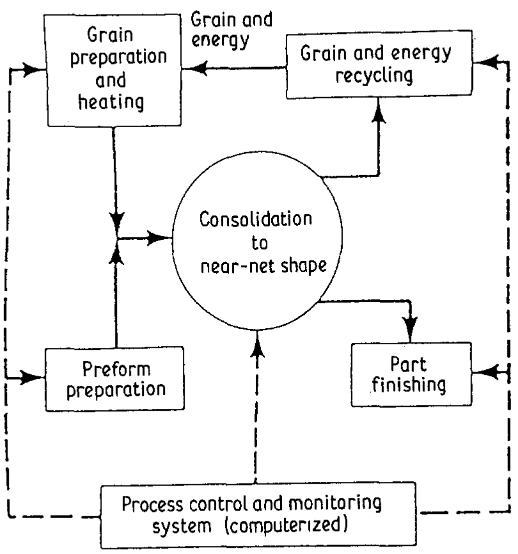

Figure 6 Flow chart of the Ceracon process [46].

2.2.2. High energy–high rate processes

An approach which has been successfully utilized to consolidate rapidly quenched powders containing a fine distribution of ceramic particulates is known as the high energy–high rate processing [52, 53]. In this approach the consolidation of a metal–ceramic mixture is achieved through the application of a high

TABLE VII Chemical compositions of aluminium powders [25]

	Cu	Mg	Zn	Si	Mn	Cr	Fe	Other
Al-Cu								
2219	6.74	–	–	–	0.4	–	0.05	0.12 V
Al-Cu-Mg								
2124	4.65	1.60	0.01	0.04	0.9	–	0.3	–
2124HP	4.65	1.5	0.02	–	–	–	0.1	–
2048	3.73	1.77	–	–	–	–	0.03	–
ACM1	2.95	1.37	–	–	–	–	–	–
ACM2	3.26	1.25	–	–	–	–	–	0.1 Zr
ACM3	3.67	1.84	–	0.14	0.2	–	0.2	0.6 Zr
Al-Mg-Si								
6061	0.35	1.19	0.02	0.77	–	0.22	0.32	–
6013	0.75	1.15	–	0.94	0.22	–	0.1	–
Al-Zn-Mg-Cu								
7075	1.5	2.5	5.5	–	–	0.30	–	–
7090	1.2	2.5	7.8	0.05	–	–	–	1.4 Co
7091	1.6	2.4	5.65	0.02	0.01	–	0.27	0.44 Co
SXA 60	1.33	2.35	9.7	0.1	–	–	0.06	–
SXA 90	1.31	2.49	7.8	–	0.02	–	0.03	–
AZMC1	–	0.79	3.56	–	–	–	–	–
AZMC2	0.68	0.98	4.18	–	–	–	–	–
MB78	2.0	2.0	7.0	–	–	–	–	0.14 Zr
Al-Li								
AL1	–	–	–	–	–	–	–	1.0
AL2	–	–	–	–	–	–	–	2.0
AL3	–	–	–	–	–	–	–	3.0
Al-Mg								
5082	–	4.5	–	–	0.7	–	–	–
Al-Cu-Mg-Li								
ACML1	0.91	0.85	–	–	–	–	–	1.66 Li
ACML2	0.63	0.68	–	–	–	–	–	1.0 Li
ACML3	1.5	1.0	–	–	–	–	–	2.8 Li
ACML4	3.0	1.0	–	–	–	–	–	1.6 Li
Other								
Al-Fe-Ce	–	–	–	–	–	–	7.7	4.2 Ce
0.3 W	–	–	–	–	–	–	5.6	4.6 Ce
Al-Fe-Mo	–	–	–	–	–	–	6.1	1.5 Mo
Al-Fe-X	–	–	–	–	–	–	4.5	4.5 Ni
1.5 Cr								
Al-Cr-X					0.8	3.8		1.3 Zr

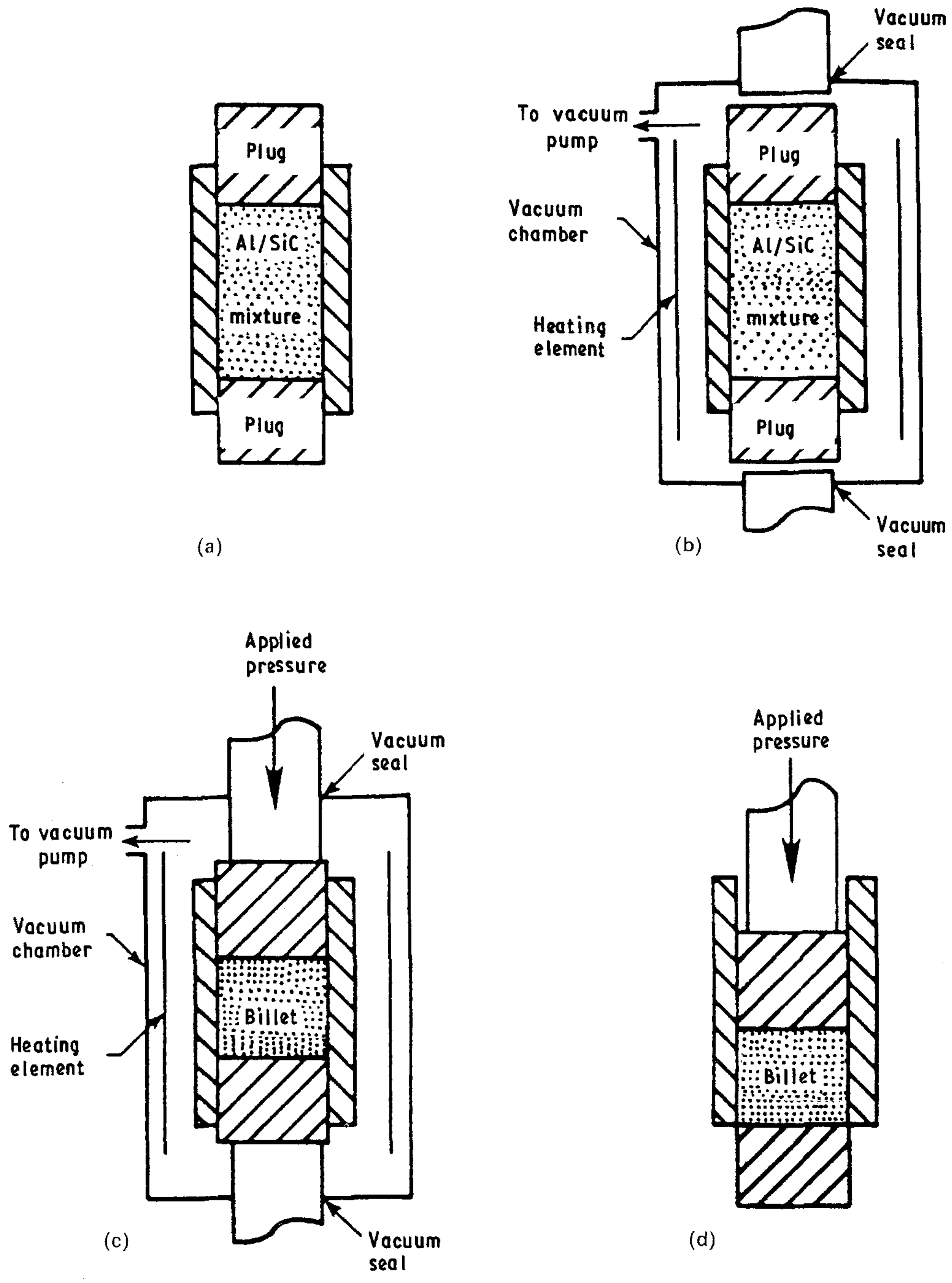

Figure 7 Schematic representation of the vacuum hot pressing technique [35].
(a) Load powder into VHP die and assemble. (b) Heat mixture/die in vacuum, outgas. (c) Compact into billet. (d) Strip billet from die.

energy in a short period of time. An examination of the open literature reveals that both mechanical energy and high electrical energy sources can be successfully utilized to consolidate metal matrix composites [52–55]. For example, Marcus *et al.* [52, 55] were able to consolidate aluminium/silicon carbide metal-matrix composites by heating a customized powder blend through a fast electrical discharge obtained from a homopolar generator. The high energy–high rate pulse (1 MJ s^{-1}) facilitates rapid heating of the conducting powder in a die with cold walls. The short time at temperature approach offers an opportunity to control: (a) phase transformations, and (b) the degree of microstructural coarsening not readily possible through standard powder processing techniques. This process has been successfully used for the manufacture of aluminium–silicon carbide and (titanium aluminide + niobium)/silicon carbide composites [54, 55]. Although the results were encouraging, extensive work still remains in order to access the potential application of this approach. An issue that remains to be addressed is the maximum thickness of a metal-matrix composite that can be processed using commercially available energy sources.

2.3. Two phase processes

Two-phase processes involve the mixing of ceramics and matrix in a regime of the phase diagram where the matrix contains both solid and liquid phases. Applicable two-phase processes include the Osprey, rheocasting and the variable co-deposition of multiphase materials (VCM).

2.3.1. Osprey^{TM} deposition

In the Osprey process, the reinforcement particulates are introduced into a stream of molten alloy which is subsequently atomized by jets of inert gas. The sprayed mixture is collected on a substrate in the form of reinforced metal matrix billet. This approach was introduced by ALCAN as a modification of the Osprey process [56–58] (Fig. 8). The process combines the blending and consolidation steps of the powder metallurgy process and promises major savings in the production of metal-matrix composites.

TABLE VIII Typical room temperature properties of PM Al/Sic composites (Ref. 48)

Material	Process	Orientation	YS (MPa)	UTS (MPa)	El. (%)	E (GPa)
6061-T6	Extrusion	—	255	290	17	70
6061-T6 (20% SiC_w)	PM/Ext	L	440	585	4	120
6061-T6 (30% SiC_w)	PM/Ext	L	570	795	2	140
6061-T6 (20% SiC_p)	PM/Ext	L	415	498	6	97

2.3.2. Rheocasting

In the rheocasting process, fine ceramic particulates are added to a metallic alloy matrix at a temperature within the solid–liquid range of the alloy. This is followed by agitation of the mixture to form a low viscosity slurry. This approach takes advantage of the fact that many metallic alloys behave like a low-viscosity slurry, when subjected to agitation during solidification. This behaviour, which has been observed for fraction solids as high as 0.5, occurs during stirring and results in breaking of the solid dendrites into spheroidal solid particles which are suspended in the liquid as fine-grained particulates [59, 60]. This unique characteristic of numerous alloys, known as thixotropy, can be regained even after complete solidification by raising the temperature. This approach has been successfully utilized in die casting of aluminium-base and copper-base alloys [60, 61].

The slurry characteristic of the matrix during stirring permits the addition of reinforcements during solidification. The ceramic particulates are mechanically entrapped initially, and are prevented from agglomeration by the presence of primary alloy solid particles. Subsequently, the ceramic particulates interact with the liquid matrix to effect bonding. Furthermore, continuous deformation and breakdown of solid phases during agitation prevents particulate

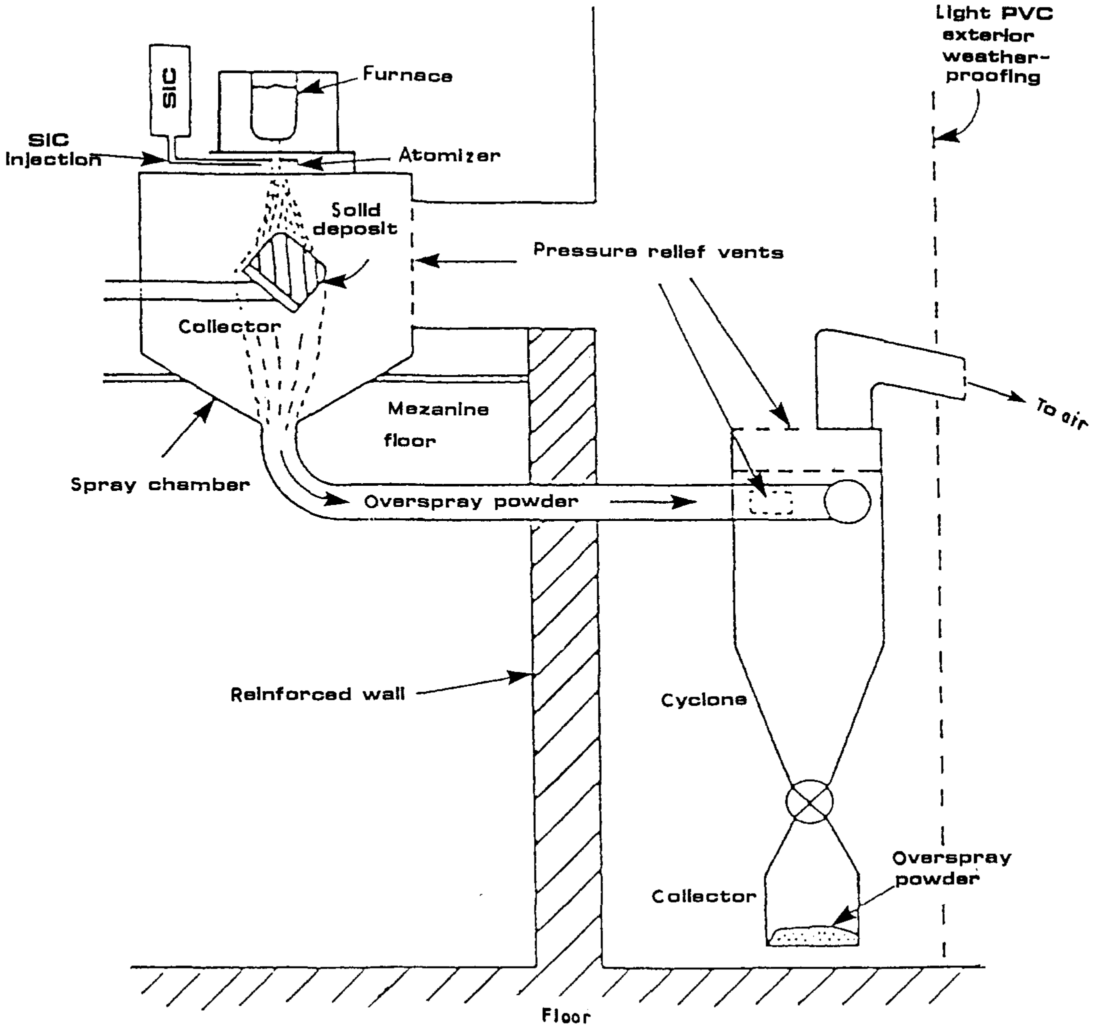

Figure 8 Schematic diagram of the modified Osprey technique [57, 58].

agglomeration and settling. This method has been successfully utilized by Mehrabian and co-workers [61, 62] to incorporate up to 30 wt % aluminium oxide and silicon carbide, and up to 21 wt % glass particles (size 14–340 µm diameter) in a partially solidified, 0.40–0.45 volume fraction solid of Al–5%Si–2%Fe alloy. The majority of the particulates were found to be homogeneously distributed in the matrix, except for the coarser particulates which settled during solidification.

2.3.3. Variable co-deposition of multiphase materials (VCM)

In the variable co-deposition of materials process, the matrix material is disintegrated into a fine dispersion of droplets using high-velocity inert gas jets (Fig. 9). Simultaneously, one or more jets of strengthening phases are injected into the atomized spray at a prescribed spatial location (Fig. 10). Interfacial control is achieved by injection of reinforcing particulates at a spatial location where the atomized matrix spray contains a limited amount of volume fraction of liquid. Hence, contact time and thermal exposure of the ceramic particulates with the partially solidified matrix are minimized, and interfacial reactions are closely controlled. In addition, tight control of the environment during processing minimizes oxidation and other environmental effects [63–65]. For situations where reactivity between the matrix material and the reinforcement is negligible, the reinforcing phases are introduced into the liquid alloy matrix prior to spray deposition [66].

In recent studies, Gupta *et al.* [63] incorporated up to 20 vol % silicon carbide particulates into an aluminium–lithium alloy matrix using the variable co-deposition technique. In this study, injection of the reinforcing phase was accomplished by entraining fine silicon carbide particulates in an inert gas stream using a suitably designed fluidized bed. Fig. 11 shows a typical optical microstructure of an aluminium–lithium/silicon carbide metal matrix composite processed by the variable co-deposition method. The experimental variables and results of image analysis of the microstructure of five independent and distinct experiments are summarized in Tables IX and X. The results given in Table X indicate that the angle of injection influences the distribution of silicon carbide particulates in the matrix. This provides convincing evidence that it is possible to tailor the resulting variations in volume fraction of silicon carbide particulates through changes in injection angle. The higher volume fraction of silicon carbide particulates observed was thought to result from the pressurization condition at the metal delivery tube. This condition is caused by the relative position of the metal delivery tube and the gas jets, and reduces the flow rate of the matrix. Consequently, effectively decreasing the aluminium lithium/silicon carbide particulate mass flow ratio resulted in higher concentration of particulates [63, 64]. With regard to size distribution of the silicon carbide particulates, the results from Table X ($d_{50} = 2.7$ µm) were found to be consistent with the initial size of the

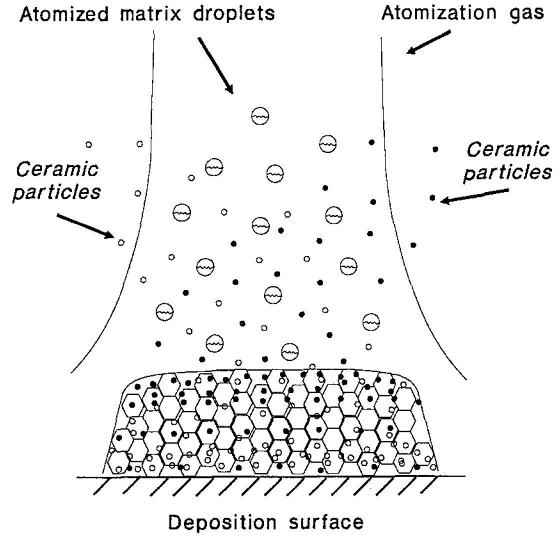

Figure 9 Schematic diagram of the variable co-deposition technique [63, 64].

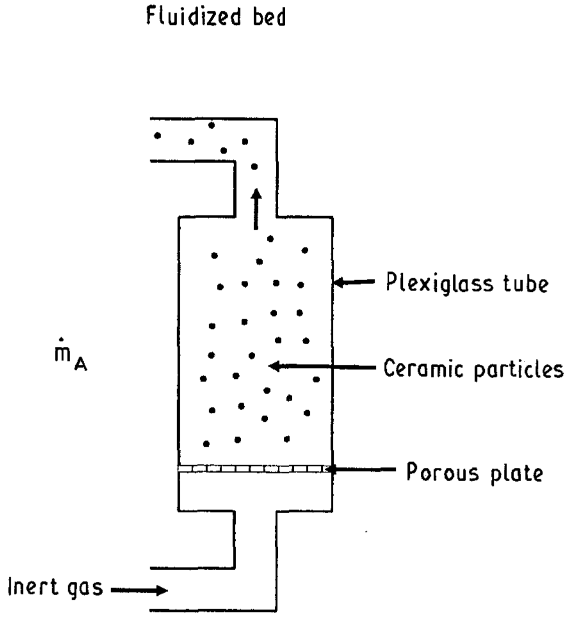

Figure 10 Schematic diagram of the fluidized bed used in the variable co-deposition technique. (■) m_A [63].

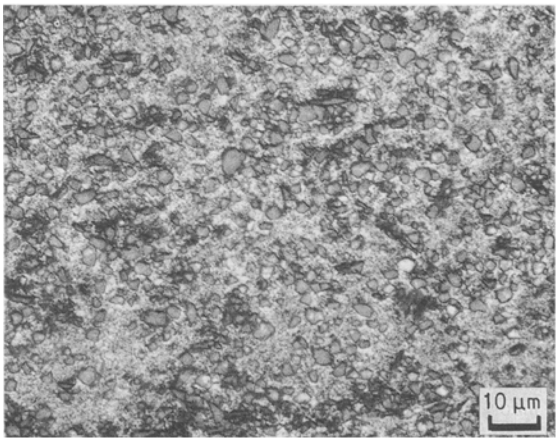

Figure 11. Microstructure of an aluminium alloy/silicon carbide metal-matrix composite produced by the variable co-deposition of materials technique [64].

TABLE IX Experimental variables used in VCM study of Al–Li–SiC$_p$ composite [63]

Variables	Experiment numbers				
	1	2	3	4	5
Matrix alloy	Al–Li	Al–Li	Al–Li	Al–Li	Al–Li
Reinforcement	SiC$_p$	SiC$_p$	SiC$_p$	SiC$_p$	SiC$_p$
Atomization pressure (MPa)	1.2	1.2	1.2	1.2	1.2
Atomization gas	Argon	Argon	Argon	Argon	Argon
Fluidized bed gas	Argon	Argon	Argon	Argon	Argon
Injection Angle[a] (deg)	30	20	90[b]	30	30
Fluidizing pressure (MPa)	0.69	0.69	0.69	0.69	0.69
Flight distance (m)	0.41	0.41	0.41	0.41	0.41
Pouring temperature (°C)	840	840	840	840	840
Metal delivery tube Diameter (mm)	3.30	3.27	3.33	3.05	3.00
Atomization nozzle Pressure condition[c] (kPa)	~ 0	6.0	~ 0	~ 0	~ 0

[a] The injection angle refers to the relative angle between the spray of SiC$_p$ and the concentric vertical axis of the atomized matrix.
[b] The 90° injection was conducted at a matrix flight distance of 0.15 m.
[c] Positive and zero values represent pressurization and metal free-fall, respectively.

TABLE X Results of image analysis of VCM processed Al–Li–SiC$_p$ composite [63, 64]

Sample no.[a]	Equivalent diameter (μm)[b]				Volume fraction (%) SiC$_p$				Inter-particle spacing, l (μm)
	Min.	Max.	Mean	S	Min.	Max.	Mean	S	
1A	0.57	09.00	2.70	2.01	1.92	08.33	3.49	1.82	14.48
1B	0.57	10.00	2.71	2.10	2.89	06.15	4.56	1.13	12.69
1C	0.57	12.00	2.10	1.76	4.40	13.44	7.89	1912	07.48
2A	N.D.[c]				–		9.60		08.71[e]
2C	N.D.	-NOT DETERMINED			–		11.65[d]		07.91[e]
3A	0.57	11.00	2.76	2.13	4.69	7.19	6.12	0.85	11.14
3B	0.57	10.00	2.86	2.12	4.38	6.10	5.13	0.50	12.62
3C	0.57	9.00	3.34	2.16	1.34	3.16	2.49	0.54	21.16
4A	0.25	13.56	1.65	2.92	18.39	24.72	20.75	2.25	18.14
4B	0.25	9.33	1.54	2.34	3.17	07.36	05.41	1.56	25.71
5A	0.25	10.68	1.61	2.79	2.60	07.63	03.70	1.54	19.99
5B	0.25	16.95	2.27	4.24	2.77	08.95	06.00	2.29	11.89
5C	0.25	18.92	2.58	4.83	0.76	15.00	05.29	5.23	10.78

[a] A, B, C designations refer to top, center and bottom regions, respectively, of the spray deposited Al–Li–SiCp.
[b] The equivalent diameter is a measure of the size of the SiC particulates.
[c] Not determined.
[d] Those values of the volume fraction were determined using quantitative metallography.
[e]

SiC$_p$ ($d_{50} = 3$ μm) used in this study. The slight reduction in particle size is attributed to difficulties associated with fluidizing the coarse silicon carbide particulates [63]. In other studies, Ibrahim and co-workers [65] incorporated up to 28 vol % silicon carbide particulates in aluminium alloy 6061 by the VCM process. The results of the ambient temperature mechanical testing (Table XI) show that the tensile properties improved with area fraction of silicon carbide particulates. This finding appears to be consistent with an increase in dislocation density, with concomitant increase in dislocation–particle interactions accompanying an increase in volume fraction. Also evident from the results summarized in Table XI, is the significant influence of thermal treatment on the mechanical behaviour of discontinuously-reinforced metal-matrix composites.

3. Conclusion

In recent years, the increasing need for high stiffness, lightweight materials for use in temperature-critical applications has resurrected interest and stimulated studies on understanding processing techniques, metallurgical characteristics and process–microstructure–mechanical property relationships relevant to metal-matrix composites. Reinforcing metal matrices with fine particulates appears to be an excellent approach to develop novel materials to meet the stringent demands of the aerospace industry for the newer generation aircraft. The particulate-reinforced composites can be fabricated using available standard or near standard metal working methods. Furthermore, problems associated with fabrication of continuously-reinforced metal-matrix composites, such as fibre damage, microstructural heterogeneity are minimized.

TABLE XI Room-temperature mechanical properties of VCM materials [65]

Material	Temper	Area fraction	σ_{UTS} (MPa)	σ_{YS} (MPa)	Elong. (%)
Unreinforced	T4	0	187	96	29.0
Unreinforced	T6	0	345	301	10.0
β-SiC$_p$	T4	10	207	96	25.0
β-SiC$_p$	T6	10	285	262	14.0
α-SiC$_p$	T4	14	196	104	23.0
α-SiC$_p$	T6	14	330	294	9.0
α-SiC$_p$	T6	17	337	299	7.0
α-SiC$_p$	T4	28[a]	252	147	12.0
α-SiC$_p$	T6	28[a]	362	322	5.0

[a] The SiC particulate size used here was 15 μm; all other tests were conducted with 3 μm particulates.

Techniques for processing particulate-reinforced metal matrix composites can be grouped into three categories: liquid-phase processes, solid-phase processes, or two-phase (solid/liquid) processes. In liquid-phase processes, fine ceramic particulates are mixed with a molten metallic matrix, using wetting agents in melt or coating the ceramic particulates. This is followed by casting the resulting composite mixture. Solid state processes involve a comprehensive blending of rapidly solidified powders with fine particulates, platelets or whiskers. The resulting composite mixture is consolidated by extrusion, forging or rolling. In two-phase processes the fine ceramic particulates are mixed with a solidifying metallic matrix. An example of the two-phase process is the variable co-deposition of multi-phase materials (VCM). In the VCM technique preforms are deposited from atomized spray of the metal matrix injected with the strengthening phases at a prescribed spatial location. The variable co-deposition of materials technique offers promise over other solid/liquid phase or liquid-phase techniques for processing discontinuously-reinforced metal-matrix composites in that contact time and thermal exposure of the ceramic particulates with the partially solidified matrix are minimized, thereby controlling interfacial reactions, and hence, mechanical properties. The development of several processing techniques has definitely stimulated the possibility of tailoring the properties of metal-matrix composites for a particular application. The processing techniques also aid in a better understanding of the roles of matrix composition, and the nature, type and morphology of the ceramic reinforcement on intrinsic microstructural characteristics of these novel engineering materials.

Acknowledgements

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