5-12-2016

Processing and Properties of Metal Matrix Composites

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PROCESSING AND PROPERTIES

OF

METAL MATRIX COMPOSITES

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MEMS 400 - Independent Study in partial fulfillment of Bachelor's Degree in Mechanical Engineering

Spring Semester 2016.

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ABSTRACT

The study was conducted to investigate the general properties and processing methods of metal matrix composites in comparison with polymer matrix composites and ceramic matrix composites. In addition, the properties of the most widely used metal matrix composites (aluminum and magnesium) were also studied. The information was collected from published online articles and journals on metal matrix composites. While metal matrix composites have been widely used in the aerospace and automobile industry, their properties are still being researched for further development and applications.

I. INTRODUCTION & BACKGROUND

Composites consist of two or more physically and/or chemically distinct materials. There are three components of a composite: matrix, reinforcement, and the interface between matrix and reinforcement. A matrix is a continuous phase of composites and serves to hold the reinforcements in predetermined orientation. A reinforcement is a stronger material distributed within the matrix. Matrix and reinforcements are chemically bonded or mechanically locked together. Matrix, reinforcements, and the interface determine the characteristics of a composite. While the characteristics of a matrix material are changed in the composite making process, those of reinforcing materials remain the same except in rare instances of processing at very high temperature.

Composites are classified based on the types of matrix and reinforcements. Composites are classified as polymer matrix composites (PMCs), metal matrix composites (MMCs), and ceramics matrix composites (CMCs) based on the type of matrix. Depending on the types of reinforcements, composites include particle reinforced composites, short fiber composites (whisker), and continuous fiber composites (sheet). The materials for reinforcements can be organic fibers, metallic fibers, ceramic fibers, and particles. The materials for matrices can be polymers, metal and its alloys, glasses, glass-ceramics, ceramics. Usually, the strength of a matrix is considerably less than that of a fiber reinforcement [1].

In PMCs, matrices are mostly cross-linked thermoset polymers (epoxy, polyester, phenolics). Glass fiber-reinforced thermoset polymers have high strength and stiffness to weight ratio, thus they are usually used in automotive components. Other matrices in PMCs include thermoplastic resins (PE, Nylon, PVC, …) [1]. In MMCs, light metals like aluminum, titanium and magnesium, and their alloys are usually used as matrices. Aluminum is most commonly used due to its excellent strength, toughness, and resistance to corrosion and abrasion [2]. In CMCs, silicon carbides are regularly used for both matrices and reinforcements. However, the silicon carbide reinforcements are of multiple forms to achieve preferred properties [5].

In particle reinforced composites, particles can be ceramics, glasses, metal, and/or amorphous materials. While the modulus of a composite is higher than that of its matrix, the permeability and ductility are lower. Therefore, particle reinforced composites can sustain higher tensile, compressive and shear stresses. Fiber reinforced composites consist of short fiber composites and continuous fiber composites. The modulus of a composite of this type is higher than that of a matrix because of the strong covalent bonds along the fiber length. The orientation of the fibers relative to one another has significant impact on the mechanical properties of the composite.

In addition to matrix and reinforcements, the interfaces also play an important role in the properties of composites. As matrix and reinforcements are not in thermodynamic equilibrium at the interface, a discontinuity of one or more material parameters (elastic moduli, strength, and chemical potential) occurs. The interfaces create a medium for the transitions and avoid a jump in material parameters between matrix and reinforcements: the transitions gradually take place over the thickness of the interface [3]. In addition, there is a chemical compound formed from the matrix materials and reinforcing materials at the interface due to the discontinuity in chemical potential. This chemical compound forms an interaction zone of which a certain thickness is desirable as long as it does not affect the properties of a composite. The discontinuity in thermal expansion coefficient of matrix and reinforcements can lead to thermal stresses in the interfacial regions of composites. Under extreme conditions, the thermal stresses result in plastic deformation in a metallic matrix and cracking in a brittle ceramic or polymeric matrix, thus changing the matrix and composite characteristics. As the reinforcement diameters decrease, the area of the interfacial regions increase, creating more medium for the chemical and mechanical interactions between matrix materials and reinforcing materials and becoming more important in governing the ultimate properties of a composite [3].

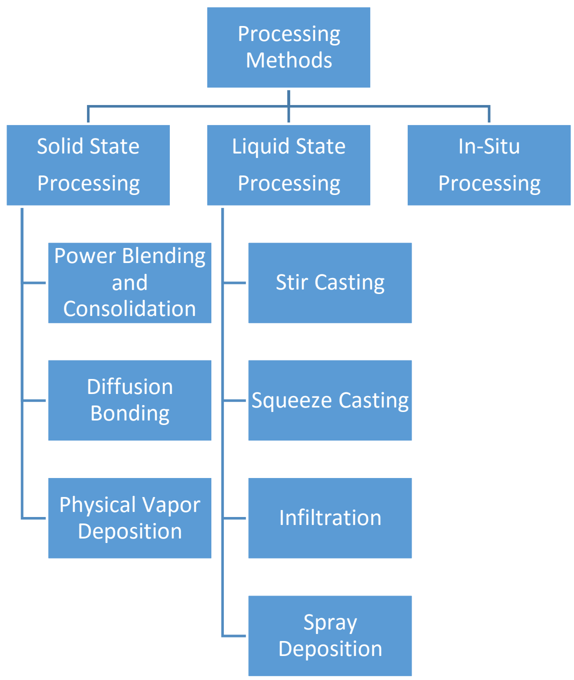
The interfacial bonding is always present between the matric and the reinforcements. However, the bonding is not the same for all types of composites. Since high stiffness and load bearing capacity are needed in PMCs and MMCs, strong bonding is usually chosen. On the other hand, weak bonding is desired in CMCs in order to deflect cracking or bridge cracking by fibers, thus increasing the toughness of the composites. The nature of bonding can be affected by multiple factors including thermal, structural, chemical, mechanical (and wettability for a liquid used in the manufacturing of the composite. In addition, the surfaces of fibers are often treated to enhance mechanical and/or chemical bonding to a desirable degree [1].

Important properties of composites are density, heat capacity, elastic moduli, strength, aging kinetics, and toughness. Rules of mixtures (ROM) calculations are used to estimate the final properties of a composite from its matrix and reinforcements. However, the behavior of composites does not always follow the ROM calculations and ROM calculations are generally valid only for continuous fiber reinforcements.

II. PROCESSING OF METAL MATRIX COMPOSITES

Processing of metal matrix composites (MMC) can be classified into three main categories:

- Solid State Processing
- Liquid State Processing
- In-Situ Processing



1. Solid State Processing

The main fabrication methods for solid state processing of metal matrix composites are powder blending and consolidation, and physical vapor deposition.

a) Powder Blending and Consolidation:

Metal alloy powder is blended with ceramic whisker/short fiber/particles in dry condition or in liquid suspension. After blending, the mixture is further processed by cold compaction, canning, degassing, and high temperature consolidation. There are some oxide particles in volume fraction of 0.05-0.5 depending on the powder and processing conditions that help dispersion-strengthening of the metal matrix composites [9]. This method is usually used for the processing of aluminum and magnesium metal matrix composites.

b) Diffusion Bonding:

The inter diffusion atoms at the metallic surfaces under pressure creates bonding between the metal matrix and fibers [14]. This fabrication method is widely used for aluminum or magnesium MMCs reinforced with continuous/discontinuous fibers.

c) Physical Vapor Deposition:

Fibers are continuously passed through a region of high partial pressure of metal to be deposited. The vapor is produced and inserted in the process, then the condensation occurs at this region to produce a coating on the fiber. The rate of deposition is about 5-10 micrometer per minute[14]. The coated fibers are then consolidated by hot pressing or hot isostatic pressing [9].

2. Liquid State Processing

a) Stir Casting:

Particulate reinforcements are mixed with liquid metal melt and the mixture then solidifies. Specifically, the pre-treated particles are inserted into the vortex of molten alloy, which is created by a rotating impeller. A problem arises during the stir casting process as the reinforcements are not uniformly distributed and form sediments in the molten alloy. Generally, up to 30% particles in the size of 5-100 micrometer can be incorporated into the metal alloy [9]. An example of this method is Al-(10-15%) B_4C MMCs.

In another variant of the stir casting method, particles are introduced into the metal alloy in the semi-solid state [9].

b) Squeeze Casting

Molten metal is introduced into an open die. The dies are then closed so that the molten metal solidifies under pressure within the dies. The heat is rapidly transferred from the molten metal to the dies under high pressure and through the contact between the metal and the die surface. As a result, a fine-grain casting with little to no pore is produced using this method [8][9][15].

c) Infiltration Process:

Liquid metal alloy is infiltrated into the porous forms of fibers/whiskers reinforcements. The volume fraction of the reinforcements usually ranges from 10-70%, depending on the level of porosity. Silica and metal-based mixtures are often employed as binder to retain the integrity and shape of the porous forms [9].

d) Spray Deposition

Particle/whisker/short fiber reinforcements are injected into the spray, creating a deposition layer of porosity of 5-10% on the metal surface. The depositions are then consolidated to full density by further processing [9].

For continuous (long) fiber reinforced metal matrix composites, matrix metals are sprayed onto the fibers. The fiber spacing and fiber layer in this processing method impact the fiber volume fraction and distribution [9].

3. In-Situ Processing

In-situ processing involves chemical reactions that result in the creation of reinforcing phase within a metal matrix. The reinforcements can be formed from the precipitation in liquid or solid. This method provides thermodynamic compatibility at the matrix-reinforcement interface. The reinforcement surfaces are also likely to be free of contamination and, therefore, a stronger matrix-dispersion bond can be achieved [9][14].

III. METAL MATRIX COMPOSITES COMPARED WITH POLYMER MATRIX COMPOSITES AND CERAMIC MATRIX COMPOSITES

The following table is a summary of the properties and processing methods used for polymer-, metal-, and ceramic- matrix composites.

	Polymer Matrix Composites	Metal Matrix Composites	Ceramic Matrix Composites
Modulus	Medium	Very High	Very High
Strength	Very High (tension) High (compression)	High (tension) High (compression)	Medium (tension) High (compression)
Density	Low	Medium	Medium
Creep Resistance	High	High	Low
Fracture Toughness	High	Medium	Low (key criterion)
Fatigue	High	Medium	Low
Fabrication Methods	- Sheet Molding - Injection Molding - Resin Transfer Molding - Prepreg Tape Lay-up - Pultrusion - Filament Winding - Thermal Forming	* <u>Solid State</u> - Powder Metallurgy - Foil Diffusion Bonding * <u>Liquid State</u> - Electro-plating/formin - Stir Casting - Pressure Infiltration - Squeeze Casting - Spray Deposition - Reactive Processing * <u>Semi-Solid State</u> - Semi-solid powder processing * <u>Vapor Deposition</u> - Physical Vapor	* <u>Conventional Ceramic Consolidation</u> - Cold-pressing and sintering * <u>Porous Pre-form Infiltration</u> - Polymer Infiltration and Pyrolysis (PIP) - Reactive Liquid Infiltration - Chemical Vapor Infiltration (CVI)

		Deposition * In-situ Fabrication	
Ease of Fabrication	Easy	Difficult	Medium
Cost	Low	Medium	High
Current Status	Extensively used	Moderately used	Rarely used

Table 1 Summary of the properties and processing methods [2][3][4][5]

IV. COMPARISON OF THE PROPERTIES OF ALUMINUM AND MAGNESIUM METAL MATRIX COMPOSITES

1. Aluminum MMCs:

Table 2 is a summary of the properties of aluminum metal and aluminum MMCs reinforced with particulates and fibers.

Properties	Matrix Metal(1)	Particulate MMCs (2)	Fiber MMCs(3)
Strength (MPa) (axial)	290	290-489	620-1240
Stiffness (GPa) (axial)	70	80-140	130-450
Transverse Strength (MPa)	290	290-480	30-170
Transverse Stiffness (GPa)	70	80-140	34-173
Plane strain fracture toughness (MPa-m)	18-35	12-35	---

Table 2 Properties of representative Aluminum MMCs [9]

(1) 6061 Aluminum

(2) 6061 Aluminum reinforced with 0-40% volume fractions of SiC particulate

(3) 6061 Aluminum reinforced with 50% volume fractions of fibers of graphite, B, SiC, alumina

Table 3 shows the properties of aluminum MMCs reinforced with fiber (50% volume fraction).

Aluminum MMCs (50% fiber volume fraction)	Tensile Strength (MPa) (axial)	Tensile Strength (MPa) (transverse)	Stiffness (GPa) (axial)	Stiffness (GPa) (transverse)
Graphite	690	30	450	34
Boron	1240	140	205	140
Silicon Carbide	1040	70	130	99
Alumina	620	170	205	140

Table 3 Properties of Fiber Reinforced Aluminum MMCs (fiber volume fraction 50%) [9]

2. Magnesium MMCs:

Table 4 provides certain properties of magnesium MMCs at different content of reinforcement.

Materials	0.2% Yield Strength (MPa)	Specific Yield Strength	Ultimate Tensile Strength (MPa)	Specific Ultimate Tensile Strength	Ductility (%)
Mg	100	58	258	148	7.7
Mg-2% Cu	281	148	335	177	2.5
Mg-4% Cu	355	170	386	184	1.5
Mg-7% Cu	---	--	433	195	1.0
Mg-2% Ni	337	177	370	194	4.8
Mg-3% Ni	420	203	463	224	1.4
Mg-6% Ni	---	--	313	131	0.7
Mg-2% Ti	163	90	248	127	11.1
Mg-4% Ti	154	81	239	126	9.5
Mg-30% SiC (Particulate)	229	105	258	118	2

Table 4 Certain properties of magnesium MMCs [11]

V. CURRENT STATUS OF METAL MATRIX COMPOSITES & FUTURE DIRECTION

As ‘green’ technologies draw significant attention around the world, manufacturing companies have utilized MMCs to produce lighter and efficient materials for fuel-efficiency automobiles and aircrafts. The new developments in hybrid and electric vehicles as well as power transmission cables have increasingly used aluminum MMCs for its light weight and high strength [2][6][16].

Even though discontinuously reinforced MMCs are the most widely used, the difficulty in fabrication has restrained its commercialization. Therefore, more processing methods with less impact on the microstructural integrity of these materials are being researched. In addition, many studies on aluminum MMCs have been conducted recently: improving damage tolerance, manufacturing high-quality reinforcements from industrial wastes and by-products, or developing aluminum MMCs based on non-standard aluminum alloys [9][16]. It is estimated that in the next 15 years, new developments of MMCs in the automobile industry will be applied to connecting rods, rocker arms, brake components, and pistons [7].

In addition, robot components, propeller shafts, electronic packaging, computer equipment, and even sporting goods have been fabricated using MMCs [6]. However, the high cost of manufacturing has hindered the wide applications and commercialization of MMCs and narrowed its applications to mostly the production of mechanical components. Recently, 3M has developed continuously reinforced aluminum MMCs for use in overhead power transmission conductors [16]. This newly developed product can be utilized as high tension wires and will significantly raise the demand for aluminum MMCs in the future. Even though titanium is heavier, more expensive, and more difficult to machine than aluminum, it retains properties at high temperature and thus its alloys are widely used in devices or machines that require high temperature properties [16].

Another rapid development in MMCs is demonstrated in the use of metallic glasses. Metallic glasses have high strength but low ductility in the bulk form. However, when metallic glasses are used as reinforcements for metal matrix, they provide stronger composites with significantly improved fracture properties. Recent investigations have been conducted to utilize metallic glasses in MMCs with higher volume fraction to provide stronger and tougher materials [16].

VI. SUMMARY AND CONCLUSION

Metal matrix composites usually consists of light-weight metals like aluminum, magnesium, or titanium, and the reinforcements are usually ceramic particulates, whiskers, or fibers. The reinforcements are an important factor in determining the properties, performance, or fabrication of the MMCs. Since there is a wide variety of types of reinforcements and fabrication methods, the data for properties of different MMCs are usually inconsistent. Generally, aluminum MMCs and magnesium MMCs have many similarities in mechanical properties and are most widely used for light-weight components in the automobile and aerospace industries. Titanium MMCs are used specifically for applications that require high temperature properties. More research investigations and development studies are being conducted to further enhance the properties and fabrication technologies, promoting the application and commercialization of MMCs in the future.

REFERENCES

[1] Callister, W Jr, Rethwisch, D. 2012. *Fundamentals of Materials Science and Engineering: An Integrated Approach*. 4st ed.. John Wiley & Sons, Inc. Hoboken. NJ.

[2] Campbell, F. 2006. *Manufacturing Technology for Aerospace Structural Materials*. 1st ed.. Elsevier Science. Amsterdam. Netherlands.

[3] Aboudi, J., Arnold, and Bednarcyk. 2012. *Micromechanics of Composite Materials: A Generalized Multiscale Analysis Approach*. 1st ed.. Butterworth-Heinemann. Oxford, UK.

[4] Unknown. Polymer Matrix Composites.
<https://www.princeton.edu/~ota/disk2/1988/8801/880106.PDF>

[5] Garcia, D. *Ceramic Matrix Composites-Manufacturing and Applications in the Automotive Industry*. University of Bristol. UK.

[6] Kainer, K., 2006. *Metal Matrix Composites. Custom-made Materials for Automotive and Aerospace Engineering.* John Wiley & Sons, Inc. Hoboken. NJ.

http://www.wiley-vch.de/books/sample/3527313605_c01.pdf

[7] Metallic Composites for the 21st Century. *Automotive Applications.*

http://www.mc21inc.com/automotive.html

[8] American Foundry Society. *Aluminum Metal Matrix Composites*

http://www.afsinc.org/content.cfm?ItemNumber=6912

[9] Surappa, M., 2003. *Aluminum matrix composites: Challenges and opportunities*.

http://link.springer.com/article/10.1007/BF02717141

[10] Dey, A. and Pandey. 2015. *Magnesium Metal Matrix Composite: A Review*.

http://www.ipme.ru/e-journals/RAMS/no_14215/07_14215_dey.pdf

[11] Ye, H. and Liu. 2004. *Review of recent studies in magnesium matrix composites*.

http://www.acetake.com/Documents/Review%20of%20Mg%20MMC.pdf

[12] Poletti, C., Balog, Schubert, Liedtke, and Edtmaier. 2008. *Production of titanium matrix composites reinforced with SiC particles*.

http://www.ifam.fraunhofer.de/content/dam/ifam/de/documents/dd/Publikationen/2008/Production_of_titanium_matrix_composites_reinforced_with_SiC_particles.pdf

[13] Arvieu, C., Even, Guillaume, Bobet, Quenisset and Chadeyron. *Processing of Carbon Fiber Reinforced Titanium Matrix Composites*.

http://www.iccm-central.org/Proceedings/ICCM12proceedings/site/papers/pap1181.pdf

[14] Kandpal, B., Kumar, Singh. 2014. *Production Technologies of Metal Matrix Composite: A Review*.

http://www.ijrmet.com/vol4issue2/spl2/4-Bhaskar-Chandra-Kandpal.pdf

[15] Total Materia. 2007. *Squeeze Casting Process: Part One.*

http://www.totalmateria.com/page.aspx?ID=CheckArticle&site=ktn&NM=172

[16] Cyriac, A. 2011. Metal Matrix Composites: History, Status, Factors and Future. Graduate College of Oklahoma State University.

https://shareok.org/bitstream/handle/11244/9914/Cyriac_okstate_0664M_11512.pdf?sequence=1