Ceramic Reinforced Metal Matrix Composite (MMC) - Processing

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ABSTRACT

Metal matrix composite (MMC) is an attractive choice for aerospace and automotive applications because of their high stiffness-to-weight ratio and excellent wear characteristics. The objective of this paper is to review recently done and on-going research on ceramic reinforced MMC. The review is limited to most commonly used metals and alloys of Fe and Al. The review focuses on the processing techniques for producing these MMC, ceramics reinforcements, compositions, microstructure evolution and parameters influencing the mechanical and wear properties.

Keywords: Aluminum, Composite, Fe, Powder metallurgy, Wear.

I. INTRODUCTION

Composite can be broadly defined as a material system, which comprises of a discrete phase (reinforcement) dispersed in a continuous phase (matrix), and which derives combination of properties, not attainable by the constituents individually.[1] These composite materials find various applications in automobile, aerospace and structural fields.[33] Composites are of different types such as: Metal Matrix Composite (MMC), Ceramic Matrix Composite (CMC), Polymer Matrix Composite (PMC), Carbon Matrix Composite and Hybrid Matrix Composites.[32] One of the challenges in the metal matrix composite (MMC) is to producing a tough yet stiff material in an attempt to reduce the formation of cracks and simultaneously improve the static and dynamic characteristics.[25] There is a need to develop damage tolerant behavior, specifically fracture toughness and ductility in MMCs. This demands appropriate selection of processing conditions, contents of reinforcement and characteristics of reinforcement.

Ceramic reinforced MMC are getting much attention because of combination of metals, which are ductile and tough with high modulus, low density and hard ceramics.[33] Commonly used metals and alloys for MMCs are aluminum[20,22,37] and aluminum alloys,[15,16,17,18,19,25,26] copper,[38] steels,[2,4,6,7,11,30,35,36] CI [28].Oxide and non-oxide ceramics, e.g. TiC,[2,4,5,6,9] TiB2,[6,11] SiC,[16] carbon nanotubes,[13] B4C,[14,15,17,20,25,26] Al2O3,[38] SiO2, and WC[28,29,30] have been incorporated in to metals and alloys matrices to produce MMCs with superior physical and mechanical properties. The structural study of a composite includes the microstructure and phase identification which could be analyzed using scanning electron microscope (SEM) and x-ray diffraction (XRD) techniques; respectively whereas mechanical study could be performed with the help of several experimental techniques such as density, hardness, wear resistance and compressive strength.[32]

Table 1: Typical materials used for composite and their properties

Material	Density (@ 20^{o}C) (g/cc)	Elastic modulus (GPa)	Melting point (^{o}C)
Al	2.7	68-70	661
Cu	8.92	110-128	1085
SS grades	7.6 – 8.0	190-210	1350-1480
Mg	1.74	45	650
Fe	7.87	211	1538
Al2O3	3.95	380	2072
B4C	2.52	450	2763
CNT	1.30-1.40	≈1000	-
C	2.18	27	3550
NbC	7.60	340	3490
SiC	3.21	324	2730
Si3N4	3.18	207	1900
TiC	4.93	270	3160
TiB2	4.50	415	2970
WC	15.63	600	2870
ZrO2	5.68	250	2715

II. ALUMINUM COMPOSITES

Aluminum is metal with superior strength to weight ratio, good thermal and electrical conductivity, good corrosion resistance, and good tribological properties.[37] But a significant drawback with aluminum metal and alloys as structural materials is their relatively low elastic modulus. This make them elastically softer compared to common structural materials like steel.[24] One strategy to stiffen these materials is through the incorporation of ceramic particles to form a metal matrix composite (MMC). Most commonly reinforced ceramics in Al an Al alloys are B4C [14,15,17,20,23,24,26] SiC[16], Al2O3[16,38], Al3Fe[37], WC[28]. Powder metallurgy (PM)[15,24,26,37] a process utilized to fabricate the composite basically involves 1) **Powder blending** in which powder of different materials having a wide range of mechanical and chemical properties are blended into a single form with the help of a ball mill. Blending leads to uniformity in shapes and homogenous mixing of powder particles which will impart a wide range of mechanical properties having homogenous characteristics throughout the material. 2) **Powder compaction** is performed with the help of a die and punch assembly which applies high pressure on the particles to form a cohesive bond between them. Compaction process is performed at room temperature. Strength develops during compaction is known as green strength. Compaction leads to reduction in the voids between the powder particles. It also produces adhesion and bonding between the particles. The compacting also facilitates the plastic deformation between the particles thereby leading to an increase in the density of the consolidated powder. 3) **Sintering** is usually done at atmospheric pressure and at an elevated temperature. Sintering temperature for the material must be below the melting temperature of the principal material but the temperature would be so much above as it will allow the diffusion between the neighboring particles. Heating process is carried out in controlled manner and in an inert atmosphere to prevent oxidation. Sintering process enhances the mechanical properties such as density of the final part by filling the incipient holes and increases the area of contact among the powder particles.

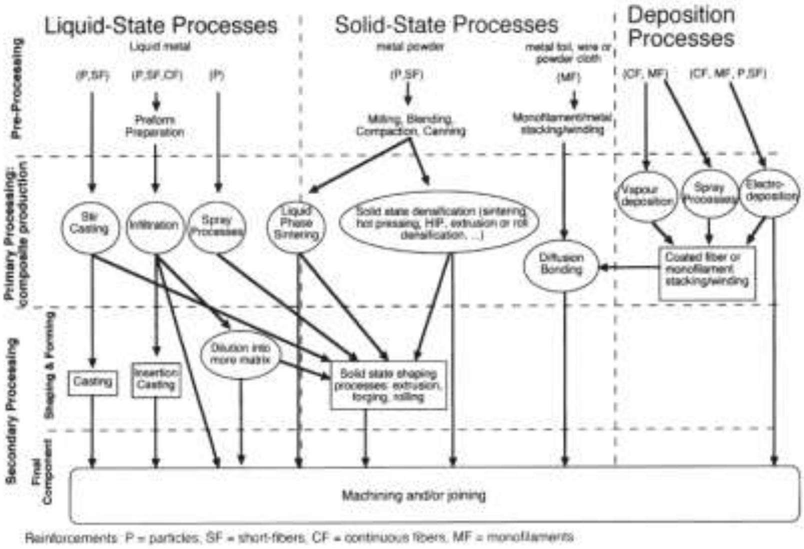

Fig.1 An overview on metal matrix composite processing

Iron Aluminide reinforced into Al matrix composite provide good friction coefficient [37], four different compositions selected as: 5, 10, 15, and 20% by weight of Al3Fe reinforcement were thoroughly mixed with 10µm Al powder in a mechanical shaker. Then cold pressed in die at 550 MPa and solid state sintered in horizontal tube furnace in a N2 atmosphere for 4 h at 550^{o}C. Strength, density, hardness, elastic modulus increases with percentage reinforcement of Al3Fe. With increasing wt. % of Al3Fe, the coefficient of friction increase because of possible increase in adhesion between the surface of the composite and the hardened steel disk. The wear rate for similar loads decreases with an increase in the reinforcement. Initially, with an increase in the sliding velocity the wear rate decreases but after attaining minima in wear, the wear rate increases with an increase in the sliding velocity.[37]

Boron carbide is one such material with a density of only 2.52 g/cm3 and an elastic modulus of 427GPa. But B4C has not been sufficiently studied and is universally used very little as a ceramic material although it has attractive properties such as excellent physical and mechanical properties and good high temperature strength.[15]

B4C reinforced composite have high potential for high hardness and stiffness. Powdered aluminum1100 of size

30‒45μm was mixed with B4C, composition varying from 0 wt.% to 6 wt.%, 10 wt.%, 15 wt.% and 25 wt.% followed by uniaxial pressing of the mixture in a rectangular die at 90MPa vacuum-sintering at 873K for 90 min. Increase in reinforcement decreases interfacial strength but modulus depends mainly upon percentage than interfacial wetting of metal-ceramic.[24] As the weight percentage of the B4C particles increases, the interfacial area between the B4C particles and matrix also increases which results in enhancement of tensile strength.[15] 5083 Al powder, B4C powder and 0.2 wt. % stearic acid was milled for 12 h in liquid nitrogen. A milling speed of 180 revolutions per minute (RPM) and a ball-to-powder ratio of 30:1 were used. Different B4C content powders were prepared. Then hot vacuum degassed at 500^{o}C for 20 h and consolidated by hot isostatic pressing (HIP) following extrusion at 400^{o}C.[26] Aluminum alloy LM25 based Al2O3 and B4C composite were fabricated by stir casting method.[23] The method involved preheating of Al ingots for 3-4 h at 550^{o}C. At the same time boron carbide and alumina powders were also preheated to 400^{o}C in the respective containers. Then, the crucible with aluminum alloy is heated to 830^{o}C while the preheated powders are mechanically mixed with each other below their melting points. There was not much difference found in the BHN of composites with 2 and 3% of B4C reinforcement. Stir casted 5% reinforced Al specimens were also tested under dry sliding conditions.[14] Extension to stir casting the ultrasonic cavitation technique [20] to distribute and disperse ceramic nano-sized particles in an aluminum melt which enhances their wettability, the degassing of liquid metals and the dispersive effects for homogenizing. Clustered particles which are produced during stir casting process can be reduced or can be broke by ultrasonic cavitation in which a probe (like titanium) is vibrated at ultrasonic frequency. Wear experiments were conducted on pin-on-disc tester based on Taguchi's L27 orthogonal array using three process parameters such as applied load, sliding velocity and distance; each varied for three levels. Loads of 10N, 20 N, 30 N; velocities of 1 m/s, 2 m/s, 3 m/s and distances of 1000 m, 1500 m, 2000 m were considered for analyzing the wear behavior of composite. Results depicted that both wear rate and coefficient of friction increases with load and decreases with velocity and distance. It was observed that, severe delamination occurred as applied load increased from 10 N to 30 N.[14] The study of micro and nano-reinforcement was carried out in which nanocomposites were found stronger and more ductile than the aluminum composites reinforced with micro-sized B4C particles. 8% reinforcement of B4C was found suitable where all properties were optimized.[20]

III. FE-COMPOSITES

Alloying of iron with carbon (in a form of graphite) can result in formation of Fe3C and/or the carbide phases (Fe3C, Fe7C3, Fe5C2), which show a tendency to amorphization and can have a very fine microstructure. So, it is possible to obtain an advanced material with high hardness, wear resistance and toughness.[13] TiB2 and TiC porous cermets (ceramic-metals) are found to be a good option for electrical applications.[6] The raw materials were titanium powder (≈19 μm), carbon powder (≈10μm) and iron boride powder (≈10μm). First pre-decided amounts of Ti, C, FeB powders were ball milled in ethanol for 72 h using a ball mill, followed by drying and sieving in order to ensure homogeneous mixing. The green compacts of milled Ti, C and FeB powders were prepared by pressing the powder uniaxially at a pressure of 300MPa. The prepared green compacts were sintered in a high vacuum furnace at 1300°C and 1350°C for 60 min. The formation of TiB2 and TiC and Fe confirmed from the X-ray diffraction analysis. A three point bending test showed increase in bending strength with sintering temperature due to reduction in porosity.[6] TiC reinforced composites were produced through conventional press and sinter P/M. Many interface debondings and pores were observed in the microstructure of composites sintered at low temperatures. Less or no interface debonding was observed in the microstructure of composite sintered at 1360°C. XRD spectra showed the Fe-Cr matrix phase in the form of elemental powder. With same TiC content carbon improved the hardness.[5]

Carbon Nanotubes (CNTs) have received an enormous degree of attention in recent years, and, in the context of composites, they are often seen as the 'next generation' of carbon fiber.[40] They have low density (range 1.5–2.0 g/cm3) the axial stiffness (approaching around 1 TPa), whilst the strength around 50 GPa. High energy planetary ball mill was used to produce mixture of CNTs (dia. 10-20 nm) and Fe powder with particle sizes of 100 nm.[13] One other significant characteristic of CNTs is their very high aspect (length to diameter) ratio which is relevant to load transfer with the matrix and, hence, effective reinforcement. [40]

Table 2: Matrix, Reinforcement and processing techniques

Matrix	Reinforcement	Processing	References
Fe	TiB2, TiC, MWNT, Al2O3, ZrO2, WC	PM, Mechanical Alloying, SPS	6,13,29,32
Fe-Cr	TiC	PM	5
SS316L	TiB2, Si3N4	PM, SPS and HIP, Powder Injection Molding	11,35
SS, Tool steel	Al2O3, TiC, Cr3C2, or TiN	HIP	2
17-4PH maraging SS	TiC	PM	4
High carbon chromium steel	WC	Vacuum infiltration casting	30
SS465	Si3N4, TiC	PM	7,9
SS440	NbC	*In-situ*	12
16Cr7Mn7Ni-steel	Mg-PSZ	Extrusion and sintering	36
Al	B4C, Al3Fe	Ultrasonic cavitation-assisted solidification, HIP, PM	20,22,37,42

LM14 aluminum alloy	B4C	Stir Casting	14
Al2024	B4C	PM, Milling and Hot extrusion	15,18
2014 Al 6061 Al	SiC, Al2O3	Casting Hot extrusion	16
Al+2 % Cu	B4C	Milling and Hot extrusion	17,44
Al alloy LM25	Al2O3, B4C	Stir casting	23
Al 1100	B4C	PM	24
Aluminum A356.1	B4C	Stir casting	25
5083 Al	B4C	PM	26
Grey CI	WC	Vacuum infiltration casting	28
Cu	Al2O3	PM	38

Multiwall CNTs are varied in the amount of 10, 20 and 30 vol.%. The phase formation with variation of milling time was studies thoroughly. α- 396 (Fe3C) and γ-(Fe3C) supersaturated solid solutions as well as Fe3C and Fe7C3 carbide phases were identified with help of SEM, TEM and XRD techniques. Use of carbon nanotubes instead of graphite in the Fe- 404C composites preparation makes the synthesis more productive due to reduction in processing time.[13] Tungsten carbide (WC) holds a leading position in industrial applications requiring good wear resistance, in particular abrasive wear resistance, since it combines high hardness, a low coefficient of thermal expansion, a certain amount of plasticity and good wettability.[28] WC particle reinforced MMCs, iron or steel matrix composites are desirable materials due to low cost and good mechanical properties. The powders of in-situ WC/Fe particulate composites containing 25vol%WC particle size of 25 µm. were mixed by using ball mill. Mixed powders were sintered by using Spark Plasma Sintering (SPS) under a pressure of 50 MPa for 5 min. Tribo-tests were performed at dry sliding condition with sliding distance of ~4632m, 120 rpm and 80N load. The dominant wear mechanism for the particulate composites was a combination of abrasive wear and oxidation wear. Large size of the WC and higher content of brittle phase Fe3W3C increased the wear rate.[29] Al2O3 and ZrO2 content have also been found good ceramic reinforcement in metal matrix. Their percentage has been varied from 5 to 30 wt% as a ceramic reinforcement. The mixture was compacted and then sintered at three different temperatures 900°C, 1000°C and 1100°C for sintering duration of 1 to 3h. In case of

Al2O3, density of composite is directly proportional to sintering time and temperature while inversely proportional to the % of reinforcement.[32]

The hardness behavior was found complex with variation of time and percentage because of two types of sintering behavior: (i) solid state sintering between the iron metal particles (ii) the reactive sintering between iron and alumina particles which lead to the formation of iron aluminate phase. In solid state sintering, the composition of ceramic phase will remain same and densification enhances but hardness of sample decreases. Whereas in reactive sintering, the ceramic phase formation leads to increase the hardness of specimen. In case of ZrO2 reinforcement there was not much variation in properties with sintering time, temperature and reinforcement percentage. Apart from this study any systematic attempts towards the study on characterization and processing of iron-based nanocomposites are not done.

IV. STAINLESS STEEL (SS) COMPOSITES

The elastic/Young's modulus of steel grades is in between 190 and 210GPa and this elastic modulus of steel changes with its chemical composition, microstructure and type of crystal structure. The hard, low density reinforcements in the steel matrix can enhance the properties to different levels but improper wetting and reaction or bonding between metal and ceramic can adversely affect the mechanical and other properties of composite.[33] Si3N4 ceramic reinforced with 465 SS powder matrix composite was fabricated by PM technique and study towards enhancing the properties of SS was done by Farid Akhtar et al.[7] (with 0–10 wt%.) The sintering temperature and time was optimized to 1300^{o}C and 60 min and it was found that relative density increases up to 5% of reinforcement and then deceases at this optimized condition. The hardness of composite showed exactly opposite behavior as that of relative density as Si3N4 particles were stable up to 2 wt% Si3N4 in the stainless steel matrix at sintering temperatures. The best combination of mechanical properties was achieved with addition of 2 wt% Si3N4 after sintering at 1300◦C for 60 min (21 HRC hardness and 1011MPa ultimate tensile strength).[7] High Pressure-High Temperature (HP-HT) and Spark Plasma Sintering (SPS) processes were used to prepare TiB2 reinforced SS316L composites. 8% of TiB2 powder with avg. size of 2.5-3.5µm was mixed with the 25µm SS316L in a Tarbula mixer which then sintered. SPS was performed at 1100^{o}C and 35MPa pressure and for HP-HT the powders were first cold pressed at 100 MPa and then sintered at 1300^{o}C for 60 s at 5 and 7 ± 0.2 GPa. Density, Elastic modulus, Vickers hardness obtained for 8TiB2-SS316L composite was found 7.60 g/cc, 221±4 GPa and 1375 MPa respectively.[11] Powder injection molding (PIM) is a net-shape manufacturing technology, which combines the shaping efficiency of plastic injection molding with the capability of conventional powder metallurgy.[35] Ferritic-austenitic (<75µm), Austenitic-316L(<75µm), Superaustenitic-654SMO (<75µm) SS grades and High speed steel (<106µm), hot worked steel (<106µm), white iron (150µm) Tool steel grades were used by Pagounis et al.[2] HIP provides the additional advantage of high densified material with near net shape. 30% reinforcements of Al2O3, TiC, Cr3C2, or TiN were done by mixing and HIPing at 1180°C, 100 MPa pressure and 3 h holding time. Further heat treatment was done to avoid carburization. Wear tests revealed that a tiny volume fraction of reinforcements in the austenitic 316L stainless steel matrix composite, which has the softest matrix (85 Rockwell B), exhibits the highest wear loss. On the other hand, the duplex–30 vol.%Cr3C2 and the 654 SMO–30 vol.% TiN composites have wear resistance comparable with or exceeding that of HIPed high speed steels. The coarser reinforcement increases tensile strength of steel matrix while % of reinforcement decreases the same.[2]

A cermet (ceramic-metal) is ideally designed to have the optimal properties of both a ceramic, such as high temperature resistance and hardness, and those of a metal, such as the ability to undergo plastic deformation. 50-70% TiC reinforced steel matrix cermets were manufactured by PM technique.[5] A pin on disk tribometer was used for wear testing of the developed cermets, under 300 and 500 N, at a sliding speed of 1.6 m/s. The wear loss of each specimen was measured after sliding approximately 1000m. The hardness of the reinforced TiC-17-4PH stainless steel composite was found to be HRA 80-81.5 for 50wt% of TiC particles. While the hardness after heat treatment was found HRA 85.5-86.0. The wear loss decreases with the increase of TiC content, the best wear resistance was shown by 70wt%TiC, it was found that the higher fraction of TiC particles improves the wear resistance.[4] With the motivation of developing a new material for high wear applications in corrosive environments W.H. Kan et al.[12] fabricated 0-25% NbC reinforced SS440 matrix composite by in-situ process in arc melting furnace. Hardening heat treatment was done by heating each ingot to 1050°C followed by water quenching. Although this fabrication method expected to lead to some difference in the distribution and morphology of carbides compared to castings made in foundry conditions, the phase transformations during heat treatment and the chemistry of various phases expected to be similar. Hardness tests were used as a quick and inexpensive method for predicting wear behavior and it was shown that an increase in NbC volume fraction also increases the overall hardness of the ingots. The casting tungsten carbide particle reinforced steel-based surface composites were manufactured by using casting-infiltration method.[30] Casting tungsten carbide particle is a kind of popular reinforcement, because of its super hardness, high-temperature behavior and great wettability with molten steel. The process of Casting-infiltration for preparing particles reinforced composite has a great practical application value. This method has a number of advantages, such as the simplicity of operation, low cost, short production cycle. The Fe3W3C is the primary precipitated carbide in the matrix, and this kind of carbide has a great contribution to the hardness.[30] C. Baumgart et al.[36] investigated sintering response of steel-ceramic composite (SS-ZrO2), Steel powder (40 μm) was mixed with 3.3 wt.% Magnesia Partially Stabilized Zirconia (Mg-PSZ) powder (30 μm) and were cold extruded. Specimens were sintered in argon-atmosphere at varying temperatures (1280°C, 1350°C, 1380°C) and dwell times (40 min, 120 min). It was found that an increase of sintering temperature and time results in an enhancement of strength under tensile and compressive load.

The SS composites prepared by PM route provide better distribution of reinforcement in the matrix but lack in strengths while stir casted composite do not offer proper distribution. In result SPS and HIP processing routes are getting much more attention and are found effective.

V. SUMMARY

In this article, literature on ceramic reinforced commonly used metal matrix composites is reviewed. Important processing methods for the production of ceramic reinforced MMCs are discussed. The influence of processing method, chemical nature of reinforcements and metal matrix on the mechanical and wear properties of MMCs is highlighted. MMCs have potential to be used for mechanical components in aerospace and wear industry for superior performance, yet there is need to develop new approaches for producing MMCs. The field of nanostructured materials has wide scope for these composites. But in the end the transition of a MMC from an advanced composite material to a cost effective applications requires a large materials production capacity, cost-effective processing, and attention to design consideration based on materials durability evaluations.

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