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Production techniques and properties of particulate reinforce metal matrix composites: a review

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ABSTRACT

The production techniques intended for synthesizing the metal matrix composites (MMCs) with particle-sized reinforcements are summarized and also the influence of reinforcement particles on various properties of MMCs is discussed. Stir casting is one of the largely used production practice for such MMCs as it is economical but there is some compromise with quality of composite due to agglomeration of reinforcement particles within the matrix phase. Such problem does not occur when MMCs are fabricated using ultrasonic stir casting process, squeeze casting and powder metallurgy technique. Tensile strength and hardness of MMCs were improved by 9 to 110 % and by 5 to 120 %, respectively, by adding reinforcement (0.5% to 30%). Wear rate and corrosion rate were decreased from 5.5 to 3.7 mm^3/km and 0.0396 to 0.0178 mm/yr, respectively. But some properties like ductility, % elongation, toughness and impact strength of the composite are compromised due to the brittle nature of the reinforcement.

KEYWORDS

metal matrix composites • reinforcements • mechanical properties • stir casting • powder metallurgy

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Introduction

In aerospace and automotive industry there are always a requirement of high strength, low weight and high toughness material. Strength and toughness also have inverse relationship. So, how to get such a material? The answer is composites. Composites possess such type of exceptional combination of mechanical properties and other properties also. Two or more materials with distinct chemical compositions and phases make up a composite [1]. The matrix-phase of the composite transfers the load to the reinforcement whereas the reinforcement-phase of the composite sustains the load and provide the strength required to the composite [2]. For classification of composites refer to Fig. 1. Aluminium, copper, magnesium and titanium are most commonly used matrix materials in fabrication of metal matrix composites (MMCs) whereas the reinforcement material can either be metal or non-metals like ceramics and organic materials [3,4]. Various kinds of reinforcement materials that are used in MMCs are summarized in Table 1. Using coated graphite (Gr) particles as reinforcement and Aluminium metal as the matrix, the first MMCs were created in the mid-1960s [5]. The weight percentage of matrix material in MMCs is typically greater than that of reinforcement material. With addition of reinforcement material, various material properties of MMCs can be tailored [6] like tensile strength, hardness, wear resistance, corrosion resistance, impact strength etc. The reinforcement material can either be in form of small particles, whiskers or fibers [7].

The main focus in this review is on the MMC with particle-sized reinforcements (or PMMCs) as they are cost-effective in terms of procurement and production cost. In these types of composites, the reinforcement material is in the form of small particles i.e. there is no long dimension [8]. Due to cost restrictions, MMCs find their usage mainly in structural and engineering related industries such as automobile industry, aerospace industry, ship-building industry, and sports industry where the product requires good strength with minimal density or weight [9]. MMCs are used in Boeing aircrafts (787, 777) and fighter jets (F-16). Door access panels, fuel lid cover, and rotor blades sleeve are made of MMCs. MMCs also find their applications in drive shafts, brake discs, and cylinder walls in an automobile. Sports products like track shoes, tennis rackets, and golf sticks can also be made using MMCs [10,11].

The problems with conventional processing of MMCs are agglomeration of particles, low density, low wettability between matrix and reinforcement material and thermal instability due to different coefficient of thermal expansion [12,13]. To overcome such issues various alternative fabrication methods are developed and also few modifications are made into the conventional processes like two-step stir casting process or ultrasonic-assist stir casting process [14]. These various types of production techniques of PMMCs, their process parameters along with the influence of particle-sized reinforcements on the properties of the fabricated composites are discussed in this paper through numerous past research articles.

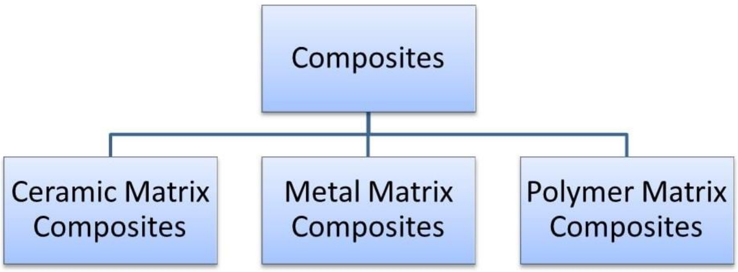

Fig. 1. Classification of composites based on matrix material

Table 1. Different reinforcement materials used in MMCs

Reinforcement Types		**Examples**
Ceramic	Borides	TiB_2, ZrB_2 [15,16]
	Carbides	SiC, TiC, WC, B_4C [17–20]
	Nitrides	Si_3N_4, BN [21,22]
	Oxides	Al_2O_3, ZrO_2, Cr_2O_3, TiO_2 [23–25]
	Carbon allotropes	Graphite, graphene, fullerene, CNT, carbon fibres, MWCNT [26–30]
Organic		Flyash, ricehusk, red mud [31–34]

Production techniques of particle-reinforced metal matrix composites

The production techniques for the particle-reinforced metal matrix composites (PMMCs) are illustrated in Fig. 2. Stir casting and squeeze casting are the most commonly used liquid-state techniques for the synthesis of MMCs, whereas powder metallurgy is preferred among the various solid-state techniques [35]. In this review paper discussions will be on stir casting, squeeze casting and powder metallurgy (PM) techniques along with recent modifications made by researchers.

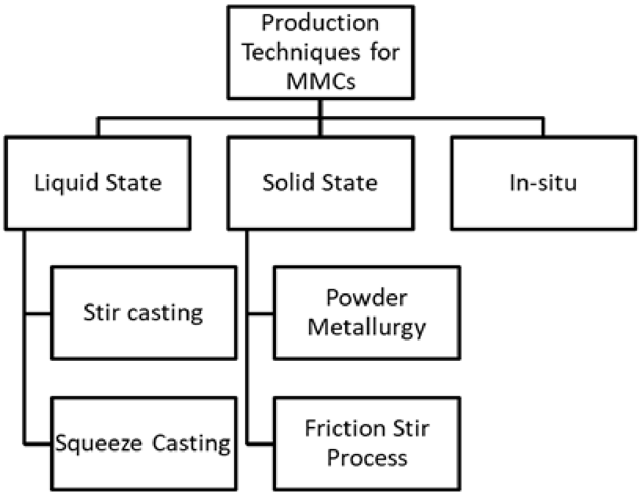

Fig. 2. Different types of production techniques for MMCs

Stir casting

One of the frequently used fabrication techniques for casting MMC with ceramic reinforcements was commenced in 1968 by S. Ray [36,37]. It is an economical process and provides better density to the composite as compared to that of solid-state techniques like powder metallurgy [38]. The stir casting setup can be seen in Fig. 3, where the composite is formed by mixing reinforcement (particles or fibres) into the liquid melt pool (matrix phase) with the help of a mechanical stirrer that is electrically fitted. The stirring action helps in improving the wettability between ceramic reinforcement and liquid metal [39]. In order to reduce blow holes and porosity in the casted composites, shielding is done using Argon or Nitrogen gas. Degassing agents such as Hexachloroethane (C_2Cl_6) or creating a vacuum condition can also remove trapped gases in the melt pool [40–42].

In 2018, Faisal and Kumar [43] fabricated an Aluminium matrix composite (AMC) with Silicon carbide (SiC) nanoparticles using a conventional stir casting approach. Aluminium alloy AA2219 was melted at 800°C and preheated SiC was added with wt. % varying from 0.5 to 2.5 %. Changes in the mechanical properties and tribological properties were observed with the change in SiC content. Mohanavel et al. (2018) [44] stir casted AA6082/Al_2O_3 nano-MMCs with reinforcement wt. % varying up to 3 %. The furnace temperature was 850 °C and the melt mixture was stirred for 20 minutes. Madhusudhan et al. (2017) [23] developed AA7068/ZrO_2 (upto 8 %) MMCs using stir casting route. C_2Cl_6 was added to the melt mixture to remove the air and other gases, i.e.

improve permeability. The mixture was stirred at 200 rpm for the homogeneous mixing of particles in the pool.

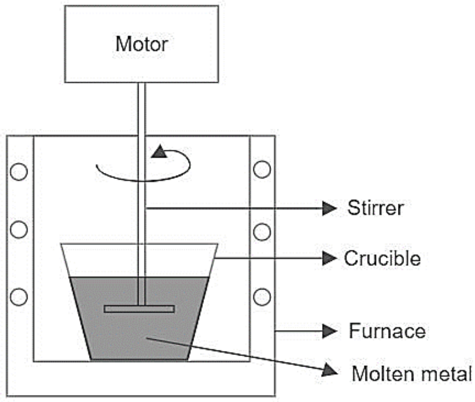

Fig. 3. A simple schematic of stir casting set-up

The problem with stir casted composites is that with an increase in reinforcement volume there is the increased agglomeration of particles within the matrix [45]. This occurrence can be a result of a decrease in wettability between particles which could reduce interfacial bonding between them that could lead to debonding of particles. The reason behind poor wettability can be the weak adhesion between the particles due to the layer of contaminants and the presence of oxide films on melt surface can hinder wettability between the liquid metal and ceramic particles which causes agglomeration at interfaces [46]. The scanning electron microscopy (SEM) test result of the fabricated AMC through stir casting route by Sharma et al. (2015b) [47] revealed the clustering of reinforcement particles in the aluminium matrix when wt. % of graphite was increased up to 12 %.

The wettability could be improved either with a coating of the reinforcement particles or with the addition of some dopants like magnesium (Mg) [48]. Few modifications in the conventional stir casting method could improve mixing of reinforcement particles preventing the formation of a cluster of particles such as using an ultrasonic probe, two-step casting, hot extrusion etc. [49,50].

In 2020, Purohit et al. [51] used ultrasonic probe assist stir casting followed by hot forging to fabricate MMC with an Aluminium alloy Al6061 as matrix and nano-Al_2O_3 (2 to 3 %) powder as reinforcement. The distribution of reinforcement particles in casted composites and hot forged, as observed through SEM test, was uniform which was further improved with heat treatment. Hashim et al. (2001) [52] did extensive research on improving the wettability between reinforcement and matrix materials. It was improved by the addition of filler material such as Mg upto 1 % by weight and also by stirring the mixture at a semi-solid state. Singh & Goyal (2016) [45] fabricated a hybrid AMC with SiC and B_4C (5 to 20 %) as reinforcements. To enhance the wettability and bonding between the two phases, Mg powder was added. Al/SiC based MMC was manufactured by Kaushik & Singhal (2018) [53] using a modified two-step stir casting procedure accompanied by mixing of 1 wt. % Mg powder. Satisfactory mixing of particles was observed till 7 wt. % of SiC reinforcement particles.

With Ultrasonic assist stir casting, manufacturing of the metal matrix composites with different metal matrix materials (like magnesium, titanium, copper etc.) becomes easier as compared to the conventional stir casting technique [54]. In 2010, Z.H. Wang et al. [55] produced Mg/SiC nano-MMC using ultrasonic stir casting technique where matrix material was Magnesium alloy AZ91. Qi et al. [56] produced Ti/TiC (10 to 20 %) composites through stir casting process, where electromagnetic stirring of melt pool was done in order to produce homogeneous mixing of TiC particles within the liquid titanium melt.

Brief information about the matrix and reinforcement material and process parameters used by various researchers in the stir casting procedure can be found in Table 2.

Table 2. Materials and process parameters used in stir casting

Matrix	Reinforcement	Process parameters	Remarks
LM4 [15]	$(TiB_2)_P$	800 °C and 500 rpm	$(TiB_2)_P$ were preheated at 600°C
AZ91 [57]	$(SiC)_P$ and Gr	680 °C	An aluminite coated stirrer was used.
Al6061 [58]	$(TiB_2)_P$	750 °C and 450 rpm	The melt was stirred in semi-solid form.
LM6 [59]	$(ZrO_2)_P$	850 °C and 950 rpm	Stirring was done with drill machine at 950 rpm for 15 minutes.
Al6061 [60]	$(ZrO_2)_P$	700-800 °C and 350 rpm	NH_4Cl and Mg were added for degassing and improvement in wettability.
Al6063-T4 [61]	$(TiO_2)_P$	850 °C and 450 rpm	Stirring was done with graphite mixer at 450 rpm for 4 minutes.
Al2219 [62]	$(TiC)_P$	750 °C and 300 rpm	C_2Cl_6 was added for degassing.
Al6101 [63]	Gr	800 °C and 550 rpm	Composites were heat treated as per T6 std.
Al+4.5%Cu [64]	$(Al_2O_3)_P$	1000 °C and 30 min	Exothermic reaction took place which formed Al-Cu phases
Al7075 [65]	$(Al_2O_3)_P$ and Gr	850 °C and 500 rpm	Spiral shaped stirrer was used and composites were heat treated afterwards.
Al6061 [66]	$(Al_2O_3)_P$	800 °C and 200 rpm	C_2Cl_6 was added for degassing.

Squeeze casting

In this method, MMC is formed by applying high pressure to the mixture of molten metal and reinforcement particles [67]. In this method, either the liquid mixture of metal matrix and ceramic or organic reinforcement are compressed together to the solid form (direct casting) or the molten metal is made to infiltrate the preform made of reinforcement material by applying pressure (indirect casting) [68]. An indirect route is generally preferred for casting MMCs with ceramic reinforcements. In comparison to stir casting, squeeze casting does not require a riser and runner thereby material wastage is reduced to the bare minimum. Also, there is improvement in the wettability between particles along with less probability of agglomeration at interfaces and low porosity due to applied pressure [69–71].

In 2020, Patil et al. [72] fabricated an Al-4.5%Cu matrix composite reinforced with Al_2O_3 fibres (10, 20 and 30 %) using the Squeeze Casting method. The alloy was melted at 750 °C and it was pressed against the preform at a pressure varying from 70–100 MPa.

Feng et al. (2008) [69] developed the hybrid composite with Aluminium borate whiskers (ABOw) and Tungsten oxide particles (WO_{3p}) as reinforcement materials and 99.6 % pure Aluminium as the matrix, using the Squeeze casting method. The pressure applied was 80 MPa. The hybrid preforms of WO_{3p} and ABOw were made using silica gel as a binder. Homogeneous mixing of both the reinforcements was observed in the hybrid composite. Gurusamy et al. (2014) [67] analysed the mechanical behaviour of the Al/10%SiC MMC developed using the Squeeze casting process, as a function of melt and die temperatures. The pressure used was 100 MPa. From the SEM test of the samples with varied melt temperatures, it was evident that the agglomeration of the particles was more at low melt temperatures and it was less at higher melt temperatures. The optimum die temperature at which the yield and impact strength were maximum was 350 °C.

Succinct information about the materials and process parameters (alloy melt temperature and pressure applied) used in squeeze casting by some of the previous researchers can be found in Table 3.

Table 3. Materials and process parameters used in squeeze casting

Matrix	Reinforcement	Process parameters	Remarks
LM6 [31]	Flyash	800 °C and 3 MPa	The stir-squeeze procedure was followed.
A356 [73]	$(SiC)_P$	800 °C, pressure: 0, 30 to 130 MPa	Low porosity, high density and better distribution of particles at high pressures above 50 MPa.
Al4032 [74]	$(SiC)_P$	750-800 °C and 100 MPa	Uniform distribution of SiC.
Al6061 [70]	$(SiC)_P$	800 °C and 100 MPa	Homogeneous distribution of reinforcement.
Al7075 [75]	$(Al_2O_3)_P$	750 °C and 125 MPa	Stir-squeeze route was used.

Powder metallurgy

It is a frequently used solid-state fabrication technique where both the matrix and reinforcement materials are in form of small particles or powder. The complete procedure for the PM technique can be seen in Fig. 4. The powders are mixed and ball milled in the required ball to powder (BPR) ratio. The mixture is then pressed with high pressure to form a green compact which then is then sintered at elevated temperatures [76]. It is a costly method but there is no wettability problem between reinforcement and matrix material, unlike the stir casting method. It also provides better distribution of particles as compared to the stir casting method [77].

Fig. 4. Steps in PM technique

In 2014, Ashwath and Xavior [78] developed an Al2900 matrix composite with SiC, Al_2O_3 and Graphene as reinforcement materials (10 to 20 %) using the PM route. The powders were all mixed and ball milled followed by compaction at 650 MPa and sintering at a temperature of 550 °C for 10 to 15 min. Al-based composites were manufactured with 0.5 to 4.5 % TiO_2 reinforcement by Nassar and Nassar (2017) [79] with help of the PM method where the powders were first ball-milled and then compacted at a pressure of 100 MPa. Sintering was done for the compacted samples at a temperature of 450 °C in the protective environment of Argon.

With some further treatment like extrusion and heat treatment after developing MMC through the Powder metallurgy technique, the hardness of composite and mixing of reinforcement particles can be improved [80]. Al-Cu/SiC composite was synthesized by Z. Wang et al. (2010) [77] using the powder metallurgy method followed by hot extrusion. Al-Cu and SiC powders were first ball milled at a BPR ratio of 4:1 followed by compaction at a pressure of 200 MPa. The compacted mixture was sintered at 420 and 570 °C and was then hot extruded. There was an improvement in the homogeneous mixing of reinforcement particles due to extrusion.

Aluminium metal matrix is mostly preferred when fabricating any MMC using conventional stir casting process but through the Powder Metallurgy process, different matrix materials can be used [81]. Some modifications can also be made in the steps of PM process for manufacturing different types of MMCs [28]. Magnesium powders usually get burnt during ball milling so the composite powders are mixed and stirred within the solvent like ethanol. The powders are then dried in vaccum followed by compaction and sintering process to create a sample of Mg based MMC [82].

Table 4. Materials and process parameters used in PM technique

Matrix	Reinforcement	Process parameters (pressure, sintering temp., atmosphere etc.)
Ti powder [18]	$(B_4C)_P$	60 MPa, 1450 °C, Sintering time: 60 min
Ti powder [24]	$(ZrO_2)_P$	700 MPa, 1100 °C, Argon, BPR- 10:1
Mg powder [25]	$(TiO_2)_P$	960 MPa, Sintering at 500 and 400 °C, hot extrusion with a ratio 16:1
Mg powder [28]	$(Fullerene)_P$	Compaction at 50 MPa and 540 °C, Sintering at 540 °C for 60 min using Argon gas for shielding.
Mg powder [82]	$(Cu)_P$ and Graphene nanoplatelets (GNP)	600 MPa, 630 °C, Argon, hot extrusion with ratio 5:1
Al powder [83]	$(SiC)_P$ and $(B_4C)_P$	150 MPa, 610 °C, Nitrogen
Al powder [84]	$(Al_2O_3)_P$	250 MPa, 600 °C, Inert, Sintering time: 300 min.
Ti powder [85]	$(AlSiCoFeNi)_P$	1000 MPa, Sintering at 600,700,800 and 900°C, Vaccum
Al powder [86]	$(Al_2O_3)_P$	500-600 °C, Argon, BPR- 10:1, Sintering time: 30-90 min.

Song et al. (2019) [76] studied the consequences of carbon-fibre powder (upto 0.8 %) on the tribological properties of the Copper MMC fabricated by the PM method. For uniform and homogeneous mixing, the powders were mixed continuously for 8 h. Then the mixture was cold pressed at 50 MPa followed by a sintering process at a temperature of about 1000 °C at 0.5 MPa. El-Tantawy et al. (2018) [22] fabricated Nickel-Copper Matrix Composite with Boron Nitride nanoparticles (1 to 5 %) as reinforcement using powder metallurgy technique. Copper and nickel powders were made from the atomization method. A very small percentage of paraffin wax (0.5 %) mixed in acetone was used as a binding agent. Uniform and homogeneous distribution of boron nitride particles was found in the sintered composite. A summary of a few of the previous researches on MMCs processed using PM is given in Table 4.

Alternative techniques for processing MMCs

There are a few other techniques apart from the above three for manufacturing of MMCs such as friction stir processing (FSP) method, disintegrated melt deposition, mechanical alloying, compo-casting method, in-situ method etc.

In 2011, Ghosh and Saha [87] studied the wear behaviour of the aluminium MMC with silicon carbide (10 to 30 %) as reinforcement which was fabricated using Direct Metal Laser Sintering (DMLS) method. Dinaharan et al. (2020) [88] developed titanium-reinforced (upto 21 %) Mg-based MMC using the FSP technique. Process parameters like the number of tool passes, traverse speed of tool and volume fraction of titanium particles were altered for obtaining the uniform distribution of reinforcement and the optimum value of tensile strength.

Some of the alternate techniques are mentioned in Table 5 used in the past researches for synthesizing of MMCs.

Table 5. Alternative production techniques

Process used	**Matrix**	**Reinforcement**
Friction stir processing [89]	Al6063	$(Quartz)_P$
Disintegrated melt deposition [90]	Pure Mg	$(Fly\ ash\ waste)_P$
Investment casting [91]	Ti alloy	B_4C
Spark plasma sintering [92]	Pure Al powder	SiC_P
Compo-casting [93]	Al6061	Flyash

Effects of reinforcement particles on the properties of the MMCs

With the introduction of reinforcements, there will be few changes in the mechanical, physical and tribological properties of the MMC compared to that of monolithic metals or their alloys. Some changes are beneficial and unwanted. Few of the properties of MMCs are mentioned below:

Tensile Strength

The strength of material under the action of tensile forces is known as tensile strength. High values of tensile strength mean that the material can perform its intended function at high loading condition. It improves with the introduction of reinforcement particles as they act as barrier to the dislocation movement which increases the value of stress required for same amount of plastic deformation [55]. Reddy et al. [94] produced Al 5052 based hybrid composites using SiC and TiC particulate reinforcements. The tensile strength of hybrid MMCs were improved from 119 to 142 MPa (19.3 % increase in strength). MMCs were produced by adding Al_2O_3 to pure Mg using PM method [95]. Tensile strength was increased by 26 % (from 168 to 211 MPa) when compared to base alloy. Comparative tensile strength of different base alloys and their MMCs are demonstrated through bar graph in Fig. 5. Table 6 shows the summarized tensile strength data for various MMCs observed by past researchers.

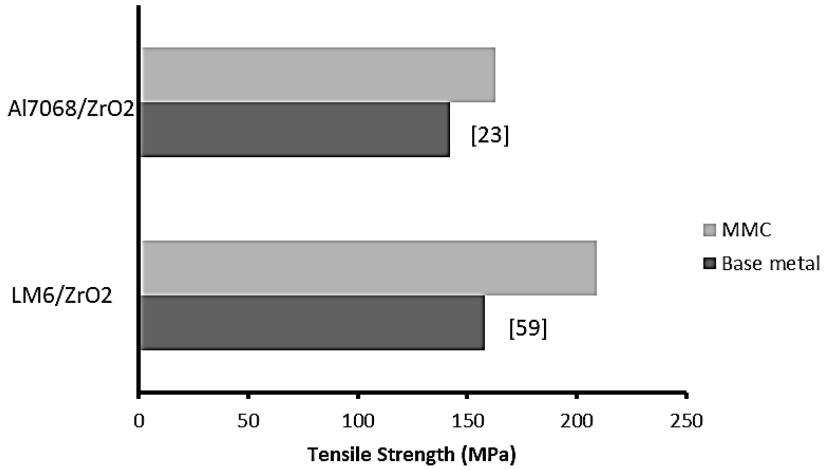

Fig. 5. Tensile strength of base metal and MMC. Based on [23,59]

Table 6. Summarized Tensile strength data for various MMCs

MMC	Method	Tensile strength, MPa	
		Base Alloy	**MMC**
Al6063/B_4C/marble dust/Gr/glass fibre [6]	Stir casting	180	249
Al6061/ZrO_2/Gr [38]	Stir Casting	128	166.3
AZ91C/SiC [41]	Stir casting	84	178
Al2219/SiC [43]	Stir Casting	80	87
AZ91D/SiC [54]	Ultrasonic Stir casting	133	191
Mg/Cu/GNP [82]	Powder Metallurgy	164	260
AZ31B/Ti [88]	Friction stir processing	226	283
Ti/B_4C [91]	Investment casting	785	1029
Mg/Al_2O_3 [95]	Powder Metallurgy	168	211
Ti/SiC [96]	Spark plasma sintering	504 ± 18	726 ± 10

Hardness

It is the resistance to indentation or scratch. Strength and hardness are correlated with each other. The ceramic reinforcements are hard and brittle in nature thus addition of even a small amount of reinforcement material improves the hardness of composites significantly [97]. The hardness value for Al7075/h-BN MMCs manufactured by Kuldeep et al. [40] was improved up to 68 BHN at 3 % h-BN. The improvement in hardness was attributed to the increase in dislocation density. Yoganandam et al. (2020) [81] analysed the mechanical properties of TMC developed using powder metallurgy method and found the rise in the values of hardness up to 5.24 % (53.97 to 56.80 BHN) with continuous mixing of boron carbide powder as reinforcement. Mg-based MMCs were manufactured with 5 % Al_2O_3 and 0-8 % SiC [98]. The hardness was increased by 16.47 % (64.53 to 75.16 HV). The hardness was increased due to grain refinement and precipitate hardening. Comparison of hardness between base metal and fabricated MMCs is illustrated in Fig. 6. Table 7 shows the summarized hardness data for various MMCs observed by past researchers.

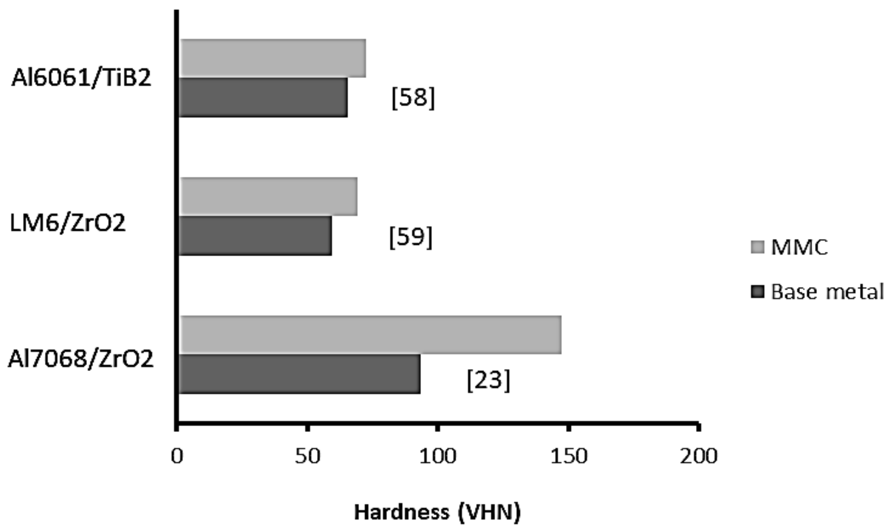

Fig. 6. Vicker's hardness comparison between base metal and MMC. Based on [23,58,59]

Table 7. Summarized Hardness data for various MMCs

MMC	Method	Hardness	
		Base Alloy	MMC
Al6063/B_4C/marble dust/Gr/glass fibre [6]	Stir casting	76 HV	88 HV
Ti/ZrO_2 [24]	Powder metallurgy	290 HV	570 HV
Mg/TiO_2 [25]	Powder metallurgy	52.41 HV	63.89 HV
LM6/flyash [31]	Squeeze casting	57.5 BHN	64 BHN
AZ91D/SiC [54]	Ultrasonic stir casting	63.5 HV	73.2 HV
Al6063/quartz [89]	Friction stir processing	62 HV	135 HV
Mg/flyash [90]	Disintegrated melt deposition	47±2 HV	112±7 HV
Al6061/SiC/Jute ash [99]	Stir casting	48 HV	66 HV

Ductility and toughness

Toughness is the measure of ability of material to absorb energy. It is high for ductile materials. With introduction of brittle reinforcement material, ductility and toughness of MMC usually decreases. The percentage elongation also decreases with increase in reinforcement quantity in the matrix of composite [45]. Deng et al. (2014) [100] manufactured magnesium based MMC with SiC particles (2, 5 and 10 %) as reinforcement and found that percentage elongation was decreased from 15 to 0.5 % with increase in SiC particles up to 10 % into the metal matrix. Mg-MMCs were produced using Vaccum stir casting with 15 % SiC added into AZ91C Mg alloy [41]. Elongation % was decreased to 1.1 from 7.2 % as a result of hard SiC particles which hindered the plastic slip movement. Aigbodion and Hassan (2007) [101] noted the decrease in the impact energy (from 17 to 10 J) of the fabricated Aluminium MMC with rise in the volume of SiC reinforcement particles upto 25 %. The elongation% was also reduced to 1.5 in 25 % SiC-MMC from 6 % in base alloy. Roseline et al. [102] developed Al/ZrO_2 MMCs and the decrease in the impact energy from 5 to 3.56 J was reported. The percent elongation for MMCs was compared with the base matrix in Fig. 7.

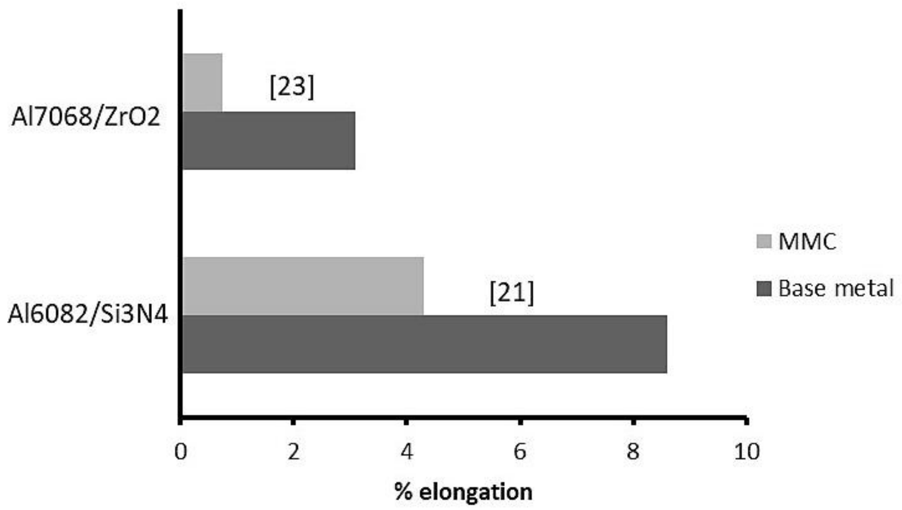

Fig. 7. Percentage elongation of Base metal and MMC. Based on [21,23]

Corrosion and wear resistance

All materials fail either due to excessive wear or under the corrosive atmosphere irrespective of loading condition. So, it's necessary to know wear and corrosion behaviour of MMCs so that their useful life can be predicted. With improvement in hardness, the resistance to wear also get enhanced [103,104]. Some materials like graphite acts as solid lubricant when added into the composite thereby improving resistance to wear to some degree [105]. To analyse wear resistance, dry sliding wear test is performed as per ASTM G99 standard [99]. With addition of reinforcements, even the corrosion resistance of developed MMCs gets improved as reinforcement materials do not corrode easily compared to the pure metals [106].

In 2017, Harti et al. [62] fabricated the Aluminium based MMCs with TiC (2, 4 and 6 %) as reinforcement to enhance the wear resistance of synthesized composites as compared to that of the monolithic metal. The dry sliding wear test was performed at different loads (0.5 to 2 kg) and speeds (600–900 rpm). The 6 % SiC-based MMC has least wear rate of 2×10^{-5} cm^3/m. Similar enhancement in the wear resistance property was found in copper based MMCs when investigated by Ali et al. (2020) [107] with addition of 4 % ZrO_2 and 4 % graphite (Gr) as reinforcement phases. The minimum wear of 122 μm was found for hybrid MMC with 4%ZrO_2 and 4% Gr at 1 kg load and 300 rpm. Change in wear rate with increase in reinforcement is evident from Fig. 8 [57], where the wear rate of Magnesium based MMCs was decreased as reinforcement weight percent was increased from 1 to 3%. Table 8 shows the summarized wear data for various MMCs observed by past researchers. From the review of these past research works, it is evident that the wear rate gets affected by the applied load, sliding distance and sliding speed. Adhesion, abrasion, ploughing and delamination are common phenomena that occur during the dry sliding wear test of MMCs samples [108–115].

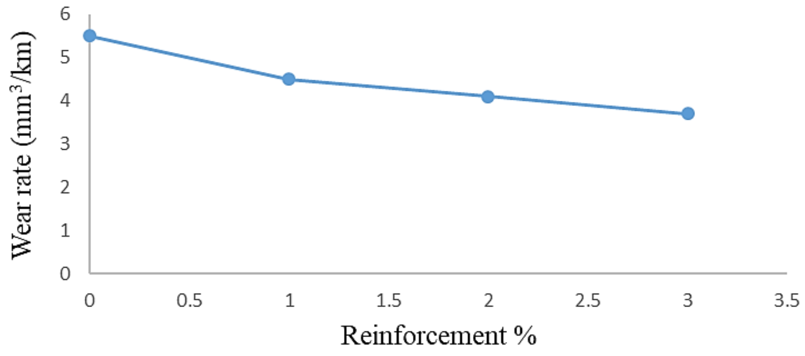

Fig. 8. Change of wear with reinforcement weight percent. Based on [57]

Table 8. Summarized wear data for different MMCs

Matrix material	Reinforcement	Wear	
		Base Alloy	MMC
LM30 [108]	18% Al_2SiO_5	$35 \times 10^{-3} mm^3/min$	$15 \times 10^{-3} mm^3/min$
A356 [109]	SiC+ MoS_2	0.038 mg/m	0.013 mg/m
Al6061 [110]	3% CeO_2+3% GNPs	$0.85\ mm^3/Nm$	$0.7\ mm^3/Nm$
Al [111]	0.1% GNPs	$3.4 \times 10^{-4} mm^3/Nm$	$1.2 \times 10^{-4} mm^3/Nm$
Al [112]	15%TiB_2	$55 \times 10^{-3} mm^3/km$	$6 \times 10^{-3} mm^3/km$
Mg [113]	0.5% ZnO	$3.3 \times 10^{-5} gm/m$	$2.3 \times 10^{-5} gm/m$
AZ91 [114]	0.15%MWCNT+0.15% GNPs	$0.002\ mm^3/m$	$0.0005\ mm^3/m$
Mg [115]	2% SiC	0.0212 gm/m	0.011 gm/m

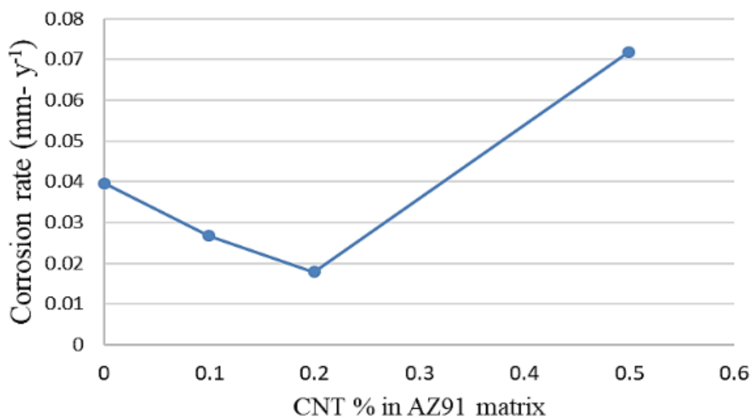

Fig. 9. Change of corrosion rate with reinforcement weight percent. Based on [29]

In 2020, Say et al. [29] studied the corrosion resistance property of magnesium matrix composites, which were reinforced with 0.1 to 0.5 % carbon nanotubes (CNTs), using Potentiodynamic scanning (PDS) tests (Fig. 9). The minimum corrosion rate (0.0178 mm-y^{-1}) was found for AZ91-based MMC reinforced with 0.2 wt. % of CNTs. An immersion test showed increased corrosion in AZ91D-ZrO_2 composites after 72 h, but it decreased after 168 h [116]. The corrosion rate for MMC was reduced to 0.23 from 1.05 mm-y^{-1} for base alloy (approximately 78 % reduction). This is due to the fine dispersion of the reinforcement, which reduced corrosion potential. Kumar et al. [106] studied the corrosion behaviour of Al6061/CeO2 MMCs at different temperatures from room temperature to 75 °C where the samples were immersed for 180 h. The corrosion was increased with increasing temperature but decreased with exposure time possibly due to anodic stabilization. Zakaria [117] performed the corrosion test on Al/SiC composites as per ASTM G31 standard using 3.5 wt. % aqueous solution at temperatures 25, 50 and 75 °C. The corrosion rate (CR) after immersion duration of 120 h for base alloy was 0.205 mm-y^{-1} and by increasing the SiC wt. % up to 15 % the CR was decreased to 0.173 mm-y^{-1} with fewer amount of pits formation. At high temperatures, CR was found to be higher due to formation of intermetallics (Al_4C_3) at the interface. Figiel et al. [118] tested Ti-based MMCs for their corrosion resistance with TiC micro (1, 10 and 20 %) and nano-powders (1, 10 and 20 %) as reinforcements. The corrosion resistance (R_{pol}) and corrosion current density (I_{cr}) for base alloy were $9.19 \times 10^3\ \Omega/\mathrm{cm}^2$ and $3.19\ \mu\mathrm{A/cm}^2$, respectively. The best corrosion resistance was observed in sample with 10 % nano-TiC powder where values of R_{pol} and I_{cr} were $43.95 \times 10^3\ \Omega/\mathrm{cm}^2$ and $1.02\ \mu\mathrm{A/cm}^2$, respectively.

Conclusions

Processing techniques of particle-reinforced MMC, influence of the particle-sized reinforcement on various properties of MMCs as well as application of MMCs were discussed briefly in the previous segments by reviewing numerous research papers. The following conclusions are made:

1. PMMCs have wide range of applications: automobile parts, aircrafts bodies, sports equipment;
2. stir casting, squeeze casting and powder metallurgy are commonly used methods for production of PMMCs;
3. the conventional stir casting method has its limitations like an agglomeration of reinforcement particles caused due to wetting problem between matrix and reinforcement particles;
4. agglomeration problems can be reduced to an extent by some modifications like adding Mg powder, using ultrasonic-assisted stir casting or squeeze casting method;
5. porosity can be reduced by using Argon gas shielding and also by adding C_2Cl_6 into melt can result in degassing;
6. the powder metallurgy process can manufacture a variety of MMCs and is not limited to just AMCs;
7. mixing of ceramic particles like SiC, Alumina, ZrO_2, B_4C etc., tends to enhance the low strain properties like hardness, UTS, and yield strength (up to 100 %) along with wear resistance and corrosion resistance of the MMCs as a result of increase in dislocation density, precipitation hardening and grain refinement; but at the same time, ductility and impact strength reduces due to the brittle nature of the reinforcement.

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