Aluminium Metal Matrix Composites Fabricated by Powder Metallurgy Techniques: A Review

Guttikonda Manohar, K. M. Pandey, and S. R. Maity

Abstract Nowaday's composite materials are at top in material selection process because of its superior mechanical, chemical and corrosive properties. But, predicting the behaviour of composites with different reinforcements and their content levels is complex because of different fabrication techniques give different properties. To use reinforcements up to its fullest in a metal matrix, suitable processing techniques have to be select so that composite with good interface bond strength and better mechanical properties can be obtained. Interface bond strength plays a major role in robustness of the composite material. Interface bond strength depends on many factors like type of reinforcement, sintering temperature, intermetallic compounds formed, etc. In this paper, a very good review is presented about composites with different reinforcements and their content levels, processing techniques, sintering temperatures, strengthening mechanisms along with theoretical equations and robustness of the composites obtained by each and every technique is included for comparison purpose.

Keywords Powder metallurgy · Composite materials · Ball milling · Intermetallic compounds · Sintering

1 Introduction

Composites play a major role in the present generation by adopting properties from added reinforcements. There are various reinforcement materials used depend on type of matrix or type of applications, generally used reinforcement materials are boron carbide (B_4C), silicon carbide (SiC), graphene, graphite, CNT, tungsten carbide (WC), titanium carbide (TiC), zirconium carbide (ZrC), etc. [1–6]. The interface binding strength between the matrix and the hard ceramic reinforcements is a crucial

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component that affects the characteristics of composite materials, especially in metal matrix materials particle reinforcements give better properties along with ductility when compared to fibre reinforcements, the reason for this is that generated contacts between matrix and reinforcements act as dislocation movement barriers [7–9], which reduces deformation capability while applying load. Compared to fibres, particle reinforcements make less interface regions and also decreased particle sizes makes high surface to volume ratios so that better load transfer mechanisms are possible. Among different available reinforcement particles, B_4C and SiC are majorly used. B_4C is used in structural applications due to high brittle nature that protects from shocks localized at high strain rates [10]. The strength of the composite increases by the addition of hard ceramic reinforcements by sacrificing the ductility nature of the material [11]. Majorly there are two methods to make nanomaterials or nanocomposites those are (a) by using external energy changing the structure of the material (conventional methods) and (b) from the powders by using mechanical alloying technique [12]. By conventional methods, agglomeration of the reinforced particles in the molten metal was the major problem due to their high surface energies which are readily to react and also factors like particle size, shape and formation of an electrical charge while stirring lead to agglomeration effects [13]. In mechanical alloying process, ball milling is the technique used to reduce particle size of reinforcements and for effective dispersion of reinforcements in matrix material. In powder metallurgy, properties of the composites mainly depend upon the quality of the green compact specimen, and this quality depends upon the densification behaviour of powders. While compaction, the compressibility of the composite powder's declines compared to its unreinforced ones [14]. Density of the green compact decides the quality of the composite while consolidating from composite powders [15], relative density increases with sintering temperature up to some level after that there are no significant changes was observed in case of plasma arc sintering (PAS) [16]. At the initial stage of compaction, sliding and rearrangement of particles are more, after that at high pressure rates, plastic deformations are predominant. At high pressure rates, densification behaviour was low compared to low pressures rates, because of hard ceramic particles clusters cause poor densification and also differences in their deformation capabilities of matrix and reinforcements [17]. As the volume fraction increases in the matrix material, agglomeration of reinforcements leads to small pores in matrix-reinforcement network. The advantage of powder metallurgy process is that chances of segregation and generation of intermetallic compounds are low. By conventional methods, sedimentation of added reinforcements was major drawback, and it affects the consistent dispersion of the reinforcement particles in the matrix material. Blended powder semisolid forming (BPSF) is a new technique which holds the advantages of casting, semisolid forming and powder metallurgy processes, in case of BPSF wetting behaviour between matrix and reinforcements was good because of liquid phase matrix [18]. Adding of Ti in the molten metal of Al increase the wettability between Al and B_4C leads to better bonding properties [19]. In traditional procedures, a temperature of around 1100 °C is required for improved bonding between Al and B_4C. There is a substantial risk of forming unneeded intermetallic compounds at that temperature, which can damage the composite material's mechanical qualities. [20].

2 Major Reported Works in Al Composites

Graphene is the most widely used reinforcement material and has very superior mechanical properties when compared to other Al composites. GNP's have high strength compared to matrix Al and its alloys, but reinforced composites show relatively low strengths. It is because of pores left during cold compaction and initiate crack propagation during fracture and also huge difference in the compressive strength and melting points makes rearrangement of particles and diffusion process difficult while sintering process makes composite porous. GNP's particle size also effects porosity levels directly and sintering temperatures decreases the porosity levels, correlation between sintering and diffusion coefficient is explained as in Eq. 1 [21].

$$D = D_o \exp(-Q/\mathrm{RT}) \quad (1)$$

D = diffusion coefficient, D_o = diffusion constant, Q = activation energy, R = Boltzmann's constant, T = sintering temperature.

Graphene-reinforced Al composites are stronger than other composites because of graphene strength. Al_4C_3 intermetallic's are formed at interfaces for Al/Graphene composites and also dislocation pileups at the grain boundaries of Al matrix also strengthen the composite material that are shown by TEM images represented in Fig. 1 [22].

Casted Al-GNP composite fabricated by ball milled, spark plasma sintered and melted along with Al melts along with subsequent rolling shows superior mechanical properties due to good interface bond strength, micro cracks are generated by rolling process at interfaces, that are shown in Fig. 2. Nano GNPs are embedded in to Al matrix, and stacking faults are generated in Al grains help in enhancement in tensile

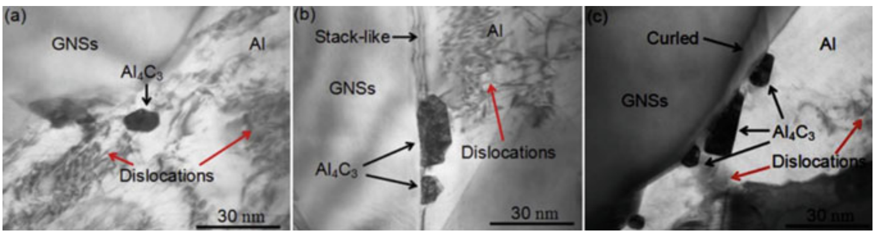

Fig. 1 Graphene-reinforced Al MMC. **a** 0.25% reinforced. **b** 0.5% reinforced. **c** 1% reinforced composites [22]

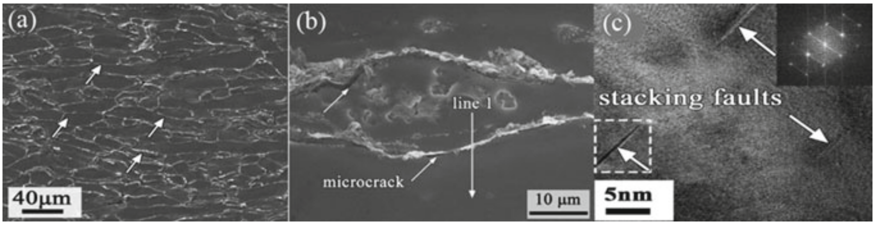

Fig. 2 **a** Uniform distribution of GNP in spark plasma sintered Al powder. **b** SEM image of composite along rolling direction. **c** Stacking faults in Al grain [23]

strength of the composite material. Nanotwin interface is also an important factor in altering the mechanical properties of the composite, and addition of graphene and rolling operations leads to generation of nanotwins in Al grains [23].

Graphene-reinforced Al composites are another trend in composites history because of its reinforcement strength (tensile strength—130GPa, elastic modulus—0.5–1 TPa). About 1 wt% reinforced graphene in Al matrix dispersed by magnetic stirring (ethanol as stirring medium) method after that cold compaction and sintering followed by hot extrusion techniques showed the mechanical properties better by 46% compared to unreinforced ones. Researches revealed that grain boundary pinning by graphene particles leads to high volume of grain boundaries which hinders the dislocation movements by this strength of the composite increases tremendously [24]. By adding graphene as reinforcement, good interface bond was formed with matrix material and Al_4C_3 compound formed at interface this phenomenon was increasing with graphene content leads to declining of its tensile strength, among the investigated reinforcement contents of 0.25, 0.5 and 1%, composite with lowest compounds formation shows better mechanical properties which is 0.25% and its tensile strength was 164 MPa [22]. By the addition of GNPs experimental density of the composite increases compared to its theoretical densities, it is because of the formation of Al oxides during sintering process. For 0.3% addition of graphene in Al matrix, there is an enhancement in UTS of 11.1%, in compression it was −7.8% and in Vickers hardness it was 11.8%. Thermal mismatch and hindered dislocations help in strengthening of composite, smaller the particle size greater the dislocation densities [21]. Few layers graphene (FLG) reinforced Al alloy shows tremendous increment in tensile strength from 350 to 700Mpa with a reinforcement content of 0.7% and elongation at failure is 4%. This was attributed to its large surface area enable to share its strength with the matrix material by effective load transfer mechanism, because of its high interfacial surface areas relation was established to predict the strength of composite as in Eq. (2) [25].

$$\sigma_c = V_r\left(\frac{S}{A}\right)\left(\frac{\tau_m}{2}\right) + \sigma_m V_m \tag{2}$$

where σ_c and σ_m = yield strength of composite and matrix, V_r and V_m = volume fraction of reinforcement and matrix, S = interfacial area, A = cross section area of FLG, τ_m = shear strength of the matrix.

GNP dispersed in Al matrix via ultrasonication and spark plasma sintering shows good dispersibility up to 1% content after those agglomerations are came in to effect due to their high surface energies, added GNP helps in pinning action of grain boundaries and restrict the grain growth while sintering process but after 3% reinforcement content average grain size increases and relative density decreases after 1% this was due to agglomeration effect. No intermetallic's were detected, this was due to low temperature and short time consolidation by spark plasma sintering process. Hardness was improved by 21.4% with 1% addition of GNP, but elastic modulus did not show any significant change, this was attributed to that major strengthening effect was by obstructing the dislocation movements rather than load transfer mechanism [26]. Another novel technique to disperse graphene in Al matrix was by coating Al particles with hexadecyl trimethyl ammonium bromide (CTAB) to obtain positive charge and graphene oxide with negative charge synthesized by modified hummers method, and then electrostatic self-assembly was used to combine graphene oxide aqueous dispersion with Al powder suspension to produce GO-Al particles. Another interesting phenomenon in this process is charge attraction between CTAB-Al powders and GO sheets which is greater than Vander Waals force makes uniform dispersion by adsorption of GO sheets on CTAB-Al particles. Structural integrity was also not affected by this process makes strength of the composite superior [27]. Another method to disperse graphene in molten Al was by preparing master alloy (Al-GNP) with graphene in it fabricated by ball milling and spark plasma sintering and then melting the master alloy along with Al melts which makes it to overcome difficulties in casting process along with subsequent rolling makes composite more strengthen and good interface bond strength. By rolling process grain refinement and GNP fibres are oriented in the rolled direction which captures the advantage of 2D graphene properties [23]. GNP dispersed by mechanical milling shows amorphous structure in the matrix material because of high impacts through ball milling defects density increases similar to this diamond and graphite also shows amorphous structures after 5000 h of milling time and in case of single walled carbon nanotube it is 50 h, compared to high energy ball milling low energy ball mills are advantageous in terms of structural integrity of the reinforcement. In the composite powder milling process, ductile phase of Al protects the GNP from collisions which delays the transformation time in to amorphous state [28]. Cold drawing also helps in dispersion of GNP effectively and creates good interface bond by eliminating GNP dense zones, but with increasing the content of GNP dispersion efficiency reduces. For 0.4% GNP after cold drawing, dense agglomerates breaks into fragments and dispersed along the drawing direction [29]. Corrosion resistance of Al-GNP composites decreases with increase in GNP content, added GNP acts as obstacles to continuous oxide film above Al particles cause initiation of corrosion from that spot. Generally, high corrosion potential and low corrosion current density represent good corrosion resistance to a material. In case of Al-GNP composites, tests revealed low corrosion resistance characteristics, this is due to cathodic behaviour of graphene particles with respect to matrix which

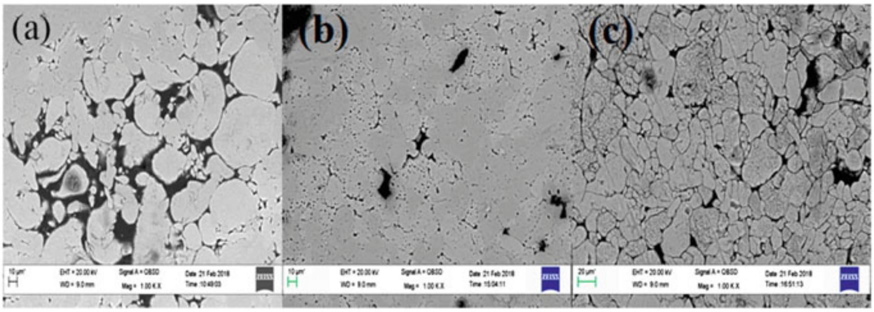

Fig. 3 SEM morphology of composites sintered by **a** conventional, **b** microwave and **c** spark plasma techniques [31]

leads to galvanic corrosion in electrolyte solution [30]. To reduce so many defects that caused by the conventional sintering processes researchers reported that microwave sintering helps in eliminating so many defects like low level intermetallic compounds generation and excellent mechanical properties. In this direction, Manohar et al. [31] conducted experiments on Al/B_4C composites with different sintering mechanisms. Microstructural tests of microwave and spark plasma sintered (SPS) composites revealed excellent increase in mechanical properties, as well as uniform distribution of reinforcements and clean interfaces without any detection of intermetallic phases through XRD analysis. Represents the XRD analysis of Al/B_4C composite subjected to different sintering mechanisms, no intermetallic's were detected in microwave and SPS composites, but AlB_2 intermetallic compound was detected in conventionally sintered composite. Fig. 3 shows the microstructural morphology of Al-B_4C composite subjected to different sintering mechanisms.

Low sintering temperatures, short sintering periods and rapid heating rates are all advantages of microwave sintering for improving the mechanical characteristics of composite materials. Experiments on AA7075/B4C/ZrC hybrid nano composites revealed that those sintered using microwave method had improved mechanical properties and that no intermetallic compounds were discovered using XRD analysis, but Al_3BC intermetallic phase was detected in conventionally sintered composite. Formation of these brittle intermetallic phases degraded the mechanical properties of conventionally sintered composite. Addition of Nano ZrC particles and microwave sintering helped in enhanced mechanical properties [32]. In a similar manner, microwave sintering on AA7075/graphite/SiC hybrid composite showed excellent mechanical properties. As graphite and SiC ceramic particles are more respond to microwaves and have high magnetic permeabilities, so that resultant mechanical properties also showed superior enhancement. Additionally, strengthening mechanisms help in strengthening the composite material. Because of the temperature mismatch between the matrix and the reinforcement particles, Orowan strengthening takes effect through appropriate dispersion of reinforcement particles and improved dislocation density strengthening. A schematic diagram representing enhanced dislocation strengthening is shown in Fig. 4 [33]. In this direction, several researchers investigated microwave sintering and the effect of different types of reinforcement particles on Al matrix composites. Different reinforcement particles include TiC [34], Al-Cu-Li particles [35], Inconel625 [36], CeO_2 [37], SiC [38], Aluminium/Tin–Bismuth [39], SiC-ZrO_2 [40], SiC-TiO_2 [41], Si_3N_4 [42], NiTi (Nitinol) [43] and Y_2O_3 [44–46] (Fig. 5).

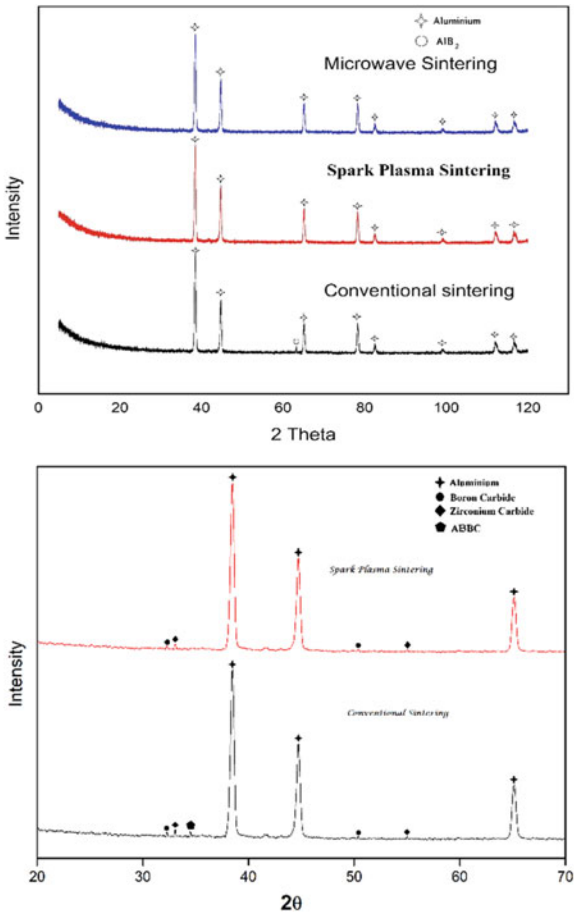

Fig. 4 XRD analysis of Al composites subjected to different sintering techniques

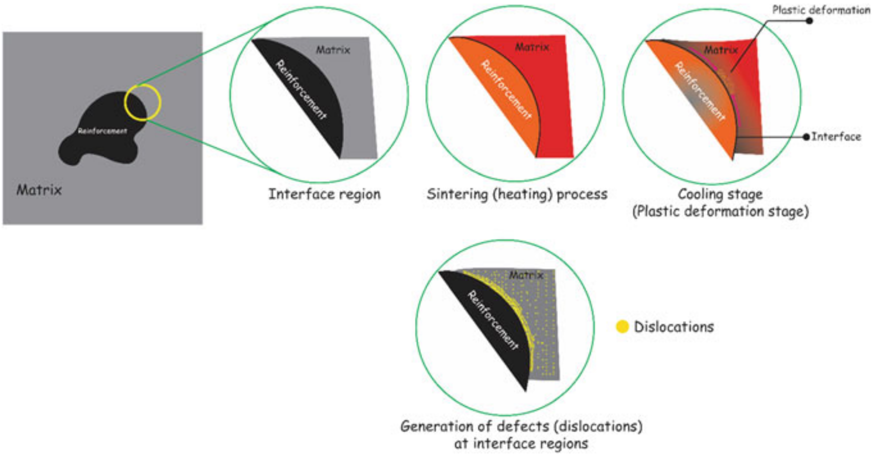

Fig. 5 Schematic diagram showing the enhanced dislocation density strengthening mechanism [33]

3 Conclusion

From the above observations and literature, it is observed that majority of the works reported by adding different reinforcement materials and fabricated through conventional sintering process showed enhanced mechanical behaviour. Intermetallic compounds generation was reported in majority of works, where fabrication process was performed through conventional sintering process. When comparing micro and nanocomposites, nanocomposites showed superior mechanical performance due to their high surface-–to-volume ratios. To enhance the performance of the composites and to retain the ductility nature of the composite materials, researchers choose advanced sintering mechanisms like microwave sintering and spark plasma sintering (SPS) as alternative to conventional sintering process. Some investigators reported that implementation of microwave sintering is recommended in case of hybrid nanocomposite where chances for the formation of intermetallic compounds.

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