



Fabrication and applications of fullerene-based metal nanocomposites: A review

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Several fabrication methods have been proposed to develop the metal matrix nanocomposites (MMNCs) reinforced by carbon nanomaterials (mostly the nanotubes, and graphene) by means of the liquid-state and the solid-state techniques. The spraying processes, the squeeze casting, the disintegrated melt deposition processes, the milling fabrication, and the friction stir processing have been used to fabricate the composite. However, the MMNCs, containing the fullerenes as reinforcement, are less known, although the properties of these objects with the predominant sp^2 bonding also extend their use in the composites. Fullerenes are hollow carbon molecules in the form of a sphere (buckyballs). Buckyballs can be essentially regarded as graphite layers, i.e., graphene sheets, wrapped into a spherical shape. Considering the staggering cost and limited availability of purified single-walled carbon nanotubes (CNTs) and graphene, fullerenes with a spherical structure offer an interesting alternative to CNTs and graphene since they are available in abundance and at a much feasible cost. Furthermore, fullerenes offer a high degree of purity and maintain their quality even during the subsequent reproduction cycles. Thus currently, the fullerenes are widely investigated and have the potential for various technical applications. A significant potential application of fullerenes would be as reinforcement in metallic alloys used in structural parts. It should be noted that buckyballs, such as C_{60} fullerenes, may be considered as fascinating reinforcements in comparison to CNT or graphene, due to their zero-dimensional geometry. They can be easily dispersed and are scarcely damaged during severe mechanical dispersion processes carried out in metal matrix composites. Fullerene has a great impact on Tribology applications due to its lubricating behavior. The spherical morphology and strong intermolecular bonding make fullerene as a lubricant material for industrial applications. This article will showcase in-depth analysis on collective information of fullerene-based nanocomposites.



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Introduction

Fullerenes are allotropes of carbon in which the molecules of carbon atoms are well connected by single and double bonds. It is observed that the fullerene molecules may be in various shapes and sizes. The reported shapes of fullerenes molecules are in the form of hollow sphere, ellipsoid, and tube shapes. The empirical formula for the fullerenes molecules is denoted as C_n or Cn and n denotes the number of carbon atoms. The first-ever literature was established by Kroto et al. [1] in 1985 which relates to C_{60} Buckminster fullerenes molecules. This unique molecule was established through vaporization of carbon from solid graphite disk through focused pulsed laser. A cluster of carbon atoms in 60 numbers was observed, thus coined as C_{60} . The C_{60} is a closed fullerene or it can be called as Buckyball. The name Buckyball was inspired from the soccer ball since it resembles the molecular structure [1]. Later, the fullerene family was extended with other forms of molecules based on shape, like Buckytubes (carbon nanotubes) which are cylindrical shaped fullerene. The existence of icosahedral symmetry in C_{60} and highest binding energy per carbon gained attention to the scientist for further research [2].

The increased demand for lightweight materials with high specific strength, stiffness, and better tribological properties in the automotive, aerospace, and defense sectors have accelerated the development and use of metal matrix nanocomposites (MMNCs) [3–6]. As material cost became a more significant consideration, the emphasis shifted toward particulate-reinforced materials, with the goal of a lower cost, high volume product that could be used in automotive and commercial aerospace applications. In past few decades, the studies related to fullerene and fullerene-based nanocomposites established their potential usages in many applications, especially as thin films, organic polymers, and organic–inorganic nanocomposites in microelectronics and optics applications are few of them [7].

Fabrication techniques for fullerene-based nanocomposites

The fabrication of nanocomposites can be established through various methods, like solid-state methods, liquid-state methods, deposition, and spraying are few of them. The mostly reported fullerene-based nanocomposites are fabricated by solid-state processing route such as powder metallurgy (PM) and friction stir processing (FSP).

One of the early-stage literatures related to synthesis of fullerene-based nanocomposites was demonstrated by Gurav et al. [8]. The studies focused on the synthesis of fullerene–rhodium nanocomposite powders by aerosol decomposition method (See Fig. 1). Two types of solution of precursor were prepared, first contained mixed fullerene extract in toluene and second contained mixed fullerene extract and [(1,5-COD)RhCl]₂ rhodium-based compound in toluene for study purpose. The synthesis of nanocrystalline composite particles of fullerene–rhodium nanocomposites demonstrated through evaporation of precursor solution which then undergone precipitation and subsequent decomposition under specific environmental conditions. In last, the powders were collected and further investigated for their features [8]. Choi et al. [9] fabricated aluminum-based fullerene-reinforced nanocomposites. The fabrication route involved in two steps: one was shattering fullerenes using two different control agents and second was disbursement of shattered fullerenes in aluminum powder using high-energy ball milling and further considered for the investigation (see Fig. 2a–c). Zuev and Ivanova [10] fabricated polyamide-6 (PA6)-based nanocomposite which reinforced with fulleroid fillers. The mechanical and electrical performances of the fabricated nanocomposites were evaluated.

El-Shamy et al. [11] fabricated a hybrid nanocomposite films based on polyvinyl alcohol/carbon quantum dots/fullerene or (PVA/CQDs/C60) through a novel casting method (See Fig. 3). This method includes dissolving particulates CQDs/C60 in deionized water then added to PVA solution at specific

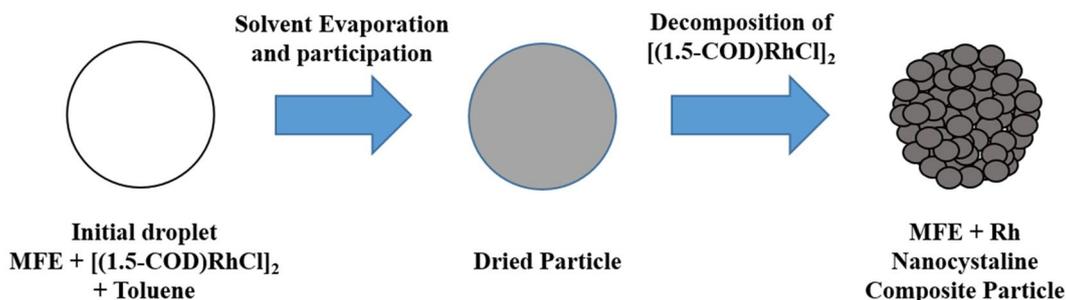


Figure 1: Schematic of generation of fullerene–rhodium nanocomposite powders via aerosol decomposition (reprinted with permission from Ref. [8]).

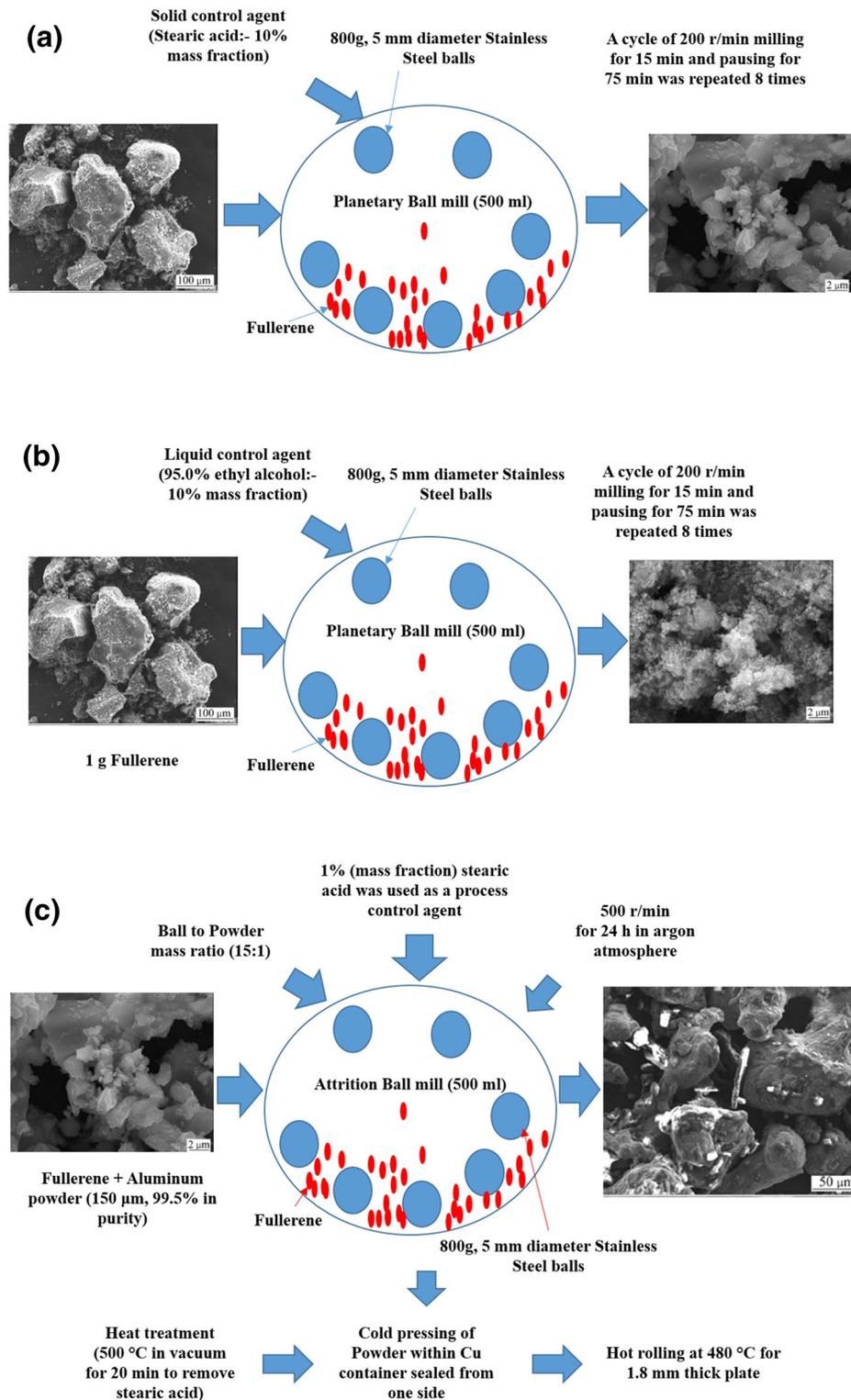


Figure 2: Step-wise (a)–(c) ball milling following by hot rolling process to fabricate fullerene-based metal nanocomposite (reprinted with permission from Ref. [9]).

temperature and time frame. As soon as some portion of the water evaporates, the solution was casted and dried [11]. A nanocomposite of fullerene reinforced with Nafion was fabricated by

Jung et al. [12] wherein a solution recasting method was considered. C₆₀ and DuPont™ Nafion PFSA (perfluorosulfonic acid) polymer dispersions are prerequisites for the fabrication processes.

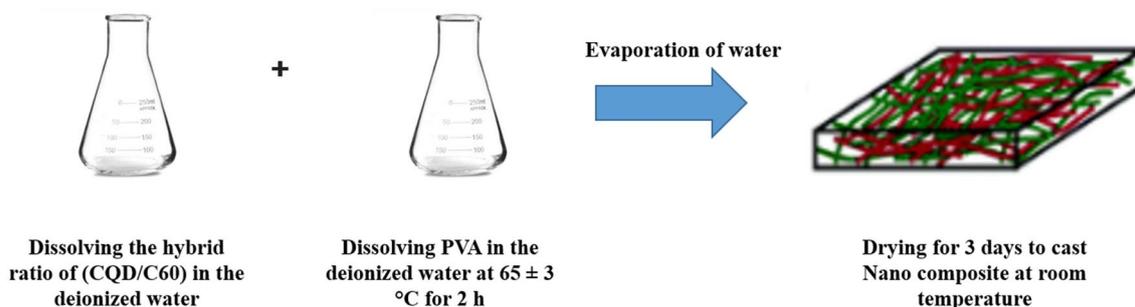


Figure 3: Casting technique to manufacture fullerene-based nanocomposite [11].

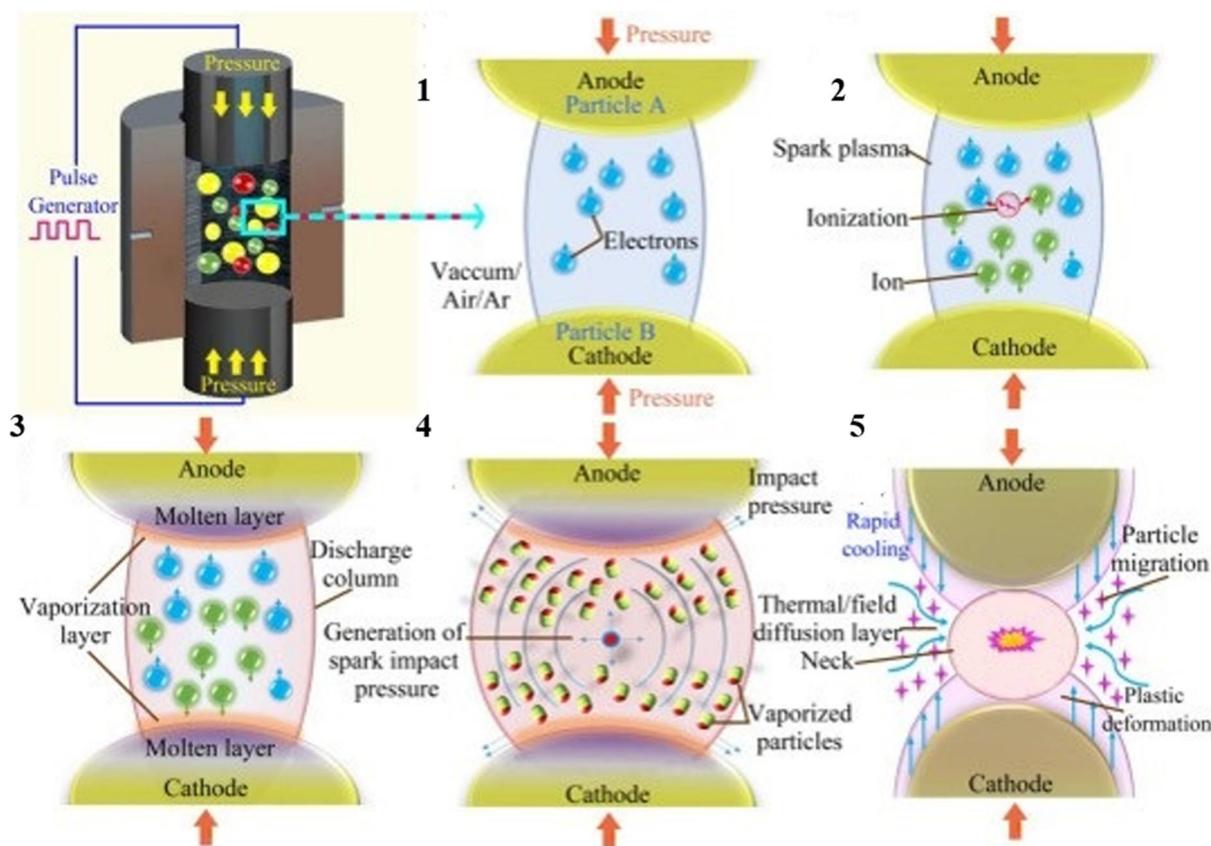


Figure 4: Spark plasma sintering process (reprinted with permission from Ref. [14]).

Vacuum-dried Nafion PFSA polymer under specific temperature and time was further used. The Nafion PFSA polymer dispersed in dimethylacetamide (DMAc) solution (stirred about 6 h at 80 °C) and subsequently C₆₀ were dispersed in orthodichlorobenzene at various concentrations 0.1% wt and 0.5% wt (stirred about 2 h at room temperature). Then these two mixtures mixed together and stirred about 24 h for stable dispersion and then dried in a casting mold at 120 °C for 12 h [12].

Santana et al. [13] studied the phase transformations during milling and sintering process of Al-C₆₀ and Fe-C₆₀. The

conventional high-energy SPEX mill was used for milling of Al-C₆₀ and Fe-C₆₀ with specific process parameters and spark plasma sintering (SPS) [14] techniques was used for sintering process (See Fig. 4). The microstructural studies were established during these two processes for understanding the influences of the milling and sintering for nanocomposite [13].

An extensive method such as powder metallurgy, sputtering, and a thin-film deposition method [15] (see Fig. 5) was studied [16]. Tin-fullerene-based nanocomposites were routed through powder metallurgy, wherein the tin powder and fullerene were

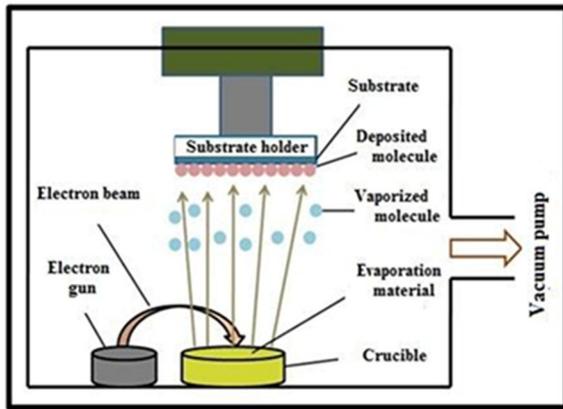


Figure 5: Thin-film deposition method [15].

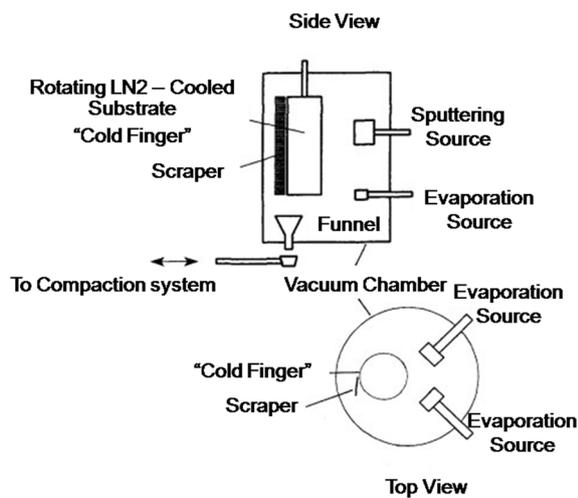


Figure 6: Schematic of the nanocomposite deposition system used to produce materials by vapor condensation and in situ compaction (rf sputtering method) (reprinted with permission from Ref. [16]).

mechanically mixed and further sintered in three stages. While in sputtering method, the same powder metallurgy procedure was used except the sintering step. In thin-film deposition method, the evaporation of tin and the sublimation of fullerenes were used to obtain thin film. For both sputtering method and deposition method, a system was developed for synthesis of nanocomposites as shown in Fig. 6 [16].

Friction stir processing (FSP) [17] was invented as grain modification technique [18–21] derived from friction stir welding [22–27]. Later, FSP is applied as composite manufacturing technique with a concept of particles insertion and subsequent distribution in base material to produce metal matrix-type

composite structure [3–6, 28–30]. Figure 8 shows FSP of composite manufacturing method, wherein a nonconsumable rotating tool is used. Figure 7a, b shows popular preprocessing steps to fill the particles/powder of materials to be inserted in the cavity. After filling powder in the slots or holes, the nonconsumable tool is plunged and moved transversely as shown in Fig. 7c that in turn helps to mix the powder with plasticized material through stirring action of tool. Distribution of powder in matrix material can be governed by viscoelastic effect of materials combined with preprocessing methods. The reinforcement of particles in matrix materials subsequently alters the properties of the processed zone. The particles are usually in nano- and/or microsize that are mixed with matrix under the effect of stirring and mixing. In fullerene-based composites fabricated by friction stir processing, the fullerene nanosized particles are reinforced into substrate material with stirring mixing process using non-consumable tool.

With reference to the nature and structure of fullerene such as smallest size among all carbon allotrope and hardest reinforcement nanoparticle, the fabrication of fullerene-based composites using FSP is an effective solution [31–36]. Fullerene/aluminum (Al) [37] and fullerene/magnesium (Mg) [38] nanocomposites were fabricated using FSP. The composite region fabricated by FSP causes onion ring-like features resulted from stirring effects, wherein the fullerene particles are distributed within those onion rings. The stirring effect causes severe deformation in base/substrate material with grain refinement. However, being one of the hardest materials, the deformation of fullerene can be avoided and that in turn led to successful dispersion in base/substrate material. The distribution of fullerene in base material is greatly governed by the material flow under the effective viscoplastic conditions that are consequently controlled by processing parameters such as rotational and travel speeds, tool design, and preprocessing insertion methods. However, limited studies were performed on these parameters. Morisada et al. [38] investigated material flow and subsequent mixing between fullerene particles (C60: 80 vol% and C70: 15 vol%) and AA5083 base material under the effect of rotational speeds (varied from 500 to 2000 rpm with an interval of 500 rpm) with groove (of 1 mm × 2 mm) type preprocessing step. Figure 8 shows variations in materials flow with mixing between fullerene and Al material under different rotational speeds with constant parameters such as triangular shape to trapezoidal shape stir zone with distinct materials mixing for rotational speed of 500 to 2000 rpm. The degree of desparation and continuous dynamic deformation increases with an increase in rotational speed during fabrication of fullerene/AA5083 that

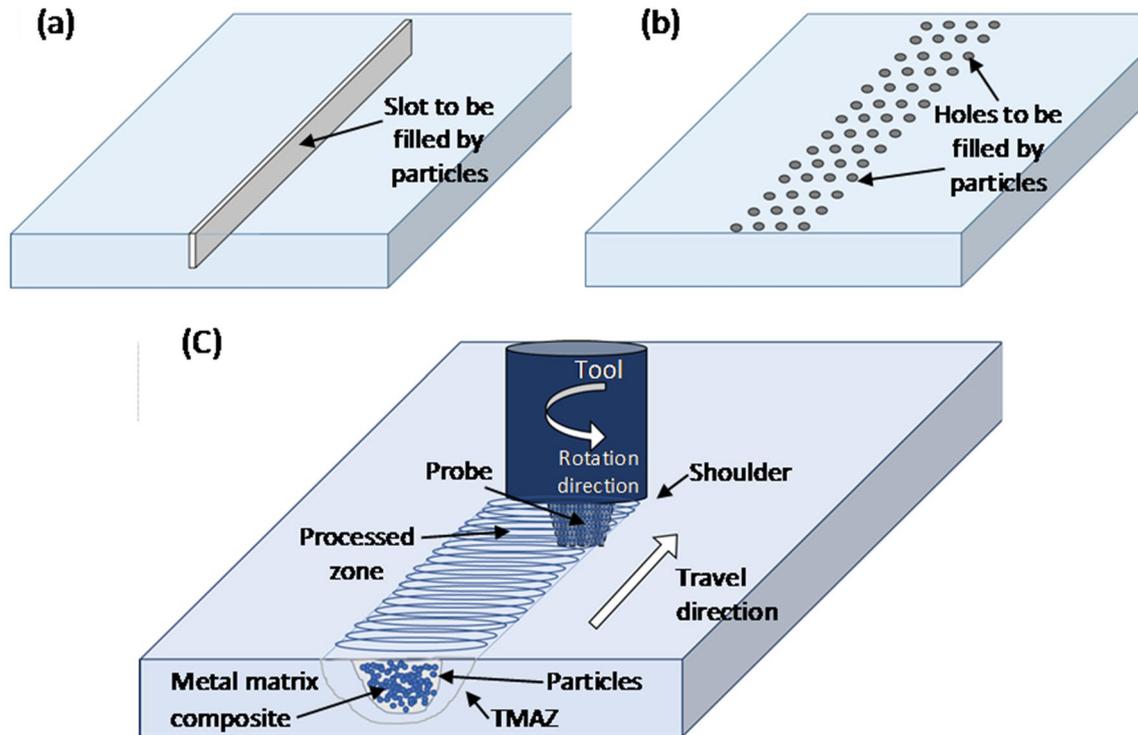


Figure 7: Friction stir processing for composite manufacturing (a) preprocessing by slot method, (b) preprocessing by hole method, and (c) processing with nonconsumable tool.

in turn resulted with more effective onion ring features and mixing between fullerene/AA5083 under trapezoidal stir zone shape. Increased rotational speed leads to increased heat input, which enhances viscoplastic behavior adequate for stirring mixing processing. Besides, low rotational speed increases flow resistance due to low heat input that in turn results in inadequate material flow and absence of onion ring features. This resistance to material flow restricts movement of fullerene materials and subsequently causes consolidation in restricted zone, which can be interpreted as nonuniform distribution of fullerene particles in substrate material. Processing conditions must be adequate (with favorable heat input to lead effective viscoplastic conditions) in order to drive fullerene distribution in work piece material. The uniform dispersion of fullerene in Al matrix is also governed by revolution pitch of tool (combination of travel and rotational speeds) and the amount of fullerene the reinforcement in the Al groove. The density of onion ring is governed by revolution pitch. The dense onion ring (i.e., small revolution pitch) with full dispersion of fullerene in Al matrix results in uniform distribution. However, microlocations within stir zone region ways show nonuniform distribution of fullerene in metal

matrix material due to complex stirring mixing phenomena. In fullerene/AA5083 composite fabricated by FSP, microlevel material mixing is shown in Fig. 9, wherein single and aggregated fullerene molecules were observed in AA5083 matrix. Similar materials mixing between fullerene and Mg alloy of AZ31 was observed as shown in Fig. 10. The grain size of the base material was greatly refined to 100 and 200 nm in case of fullerene/AZ31 and fullerene/AA5083 composite fabricated by FSP, respectively [38]. Morisada and Fuji [38] claimed that matrix grain diameter was reduced 1/800 as compared to base material microstructure. Morisada et al. [37] mentioned that grain growth is restrained by peening effect of fullerene particles that are dispersed in the Al matrix grain boundaries, which do not allow grain growth after dynamic recrystallization usually occurred in FSP region.

Powder metallurgy (PM) [39–41] is well-established fabrication method to manufacture nanocomposite materials [42, 43]. The homogenous dispersion of the fullerene particles is necessitated to achieve the best possible surface properties within the structural component. However, fullerene tendency of agglomerate leading to restricted intermixing over the entire surface area of metal. This in turn promotes the stress concentration

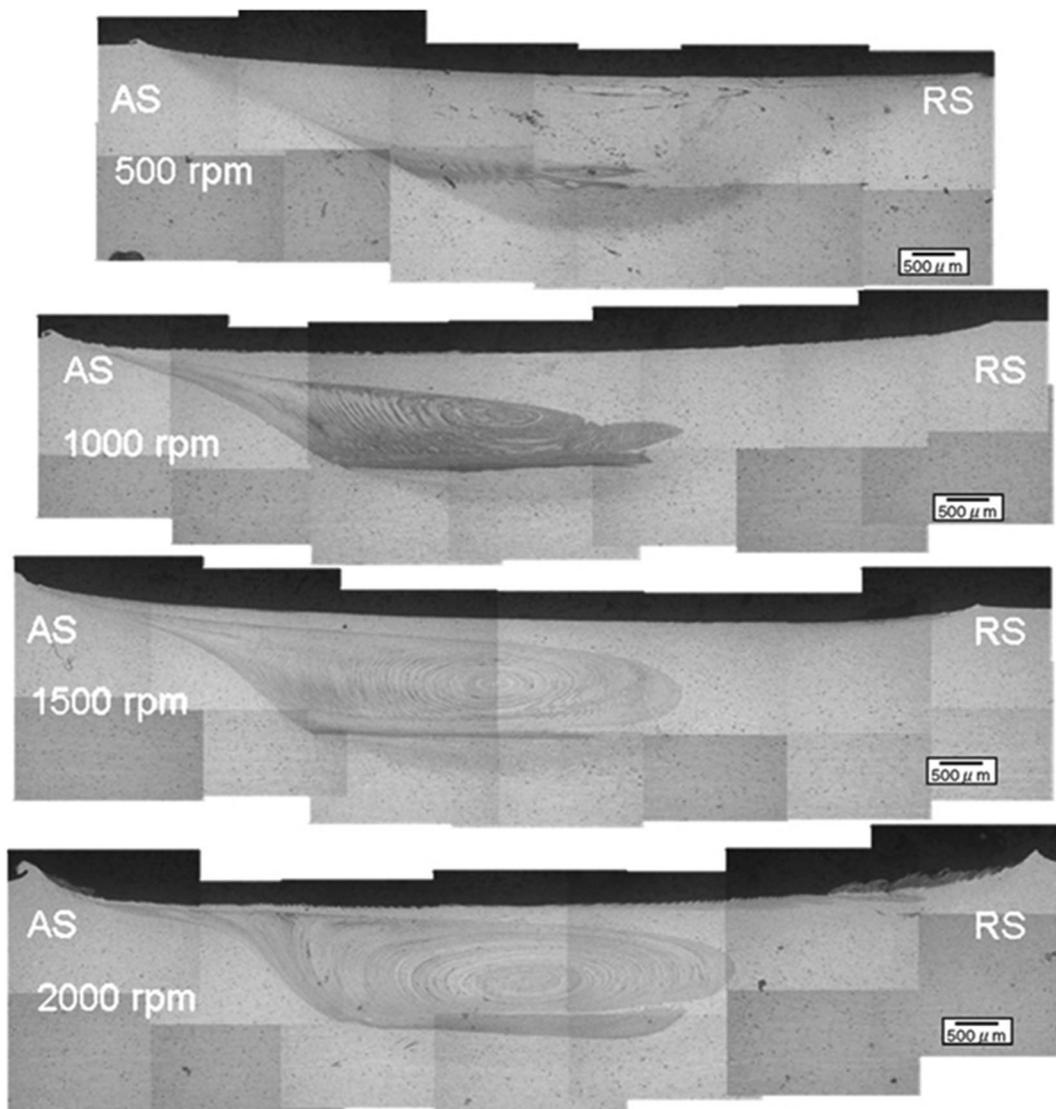


Figure 8: Materials flow with different rotational speeds for fullerene/AI FSP (reprinted with permission from Ref. [37]).

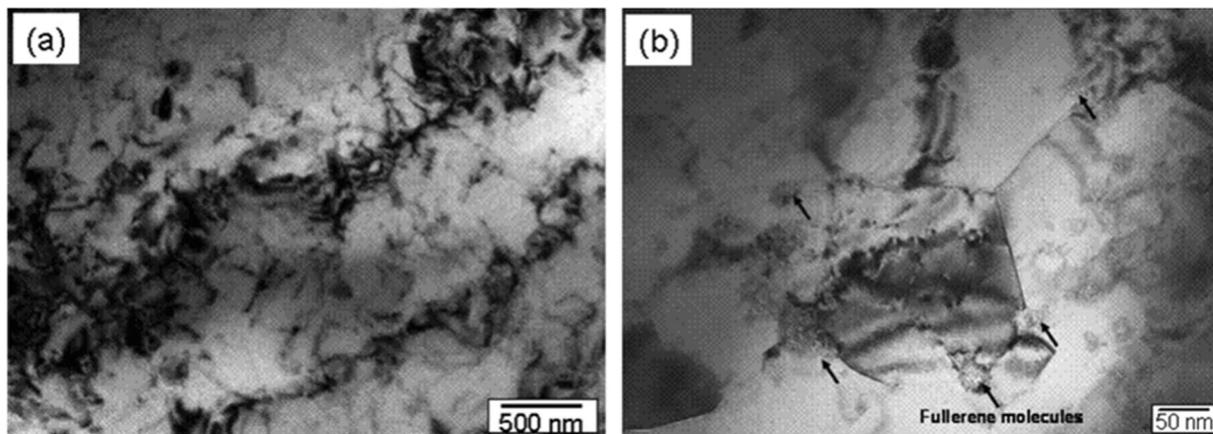


Figure 9: Materials mixing between fullerene/AA5083 (TEM images) (reprinted with permission from Ref. [37]).

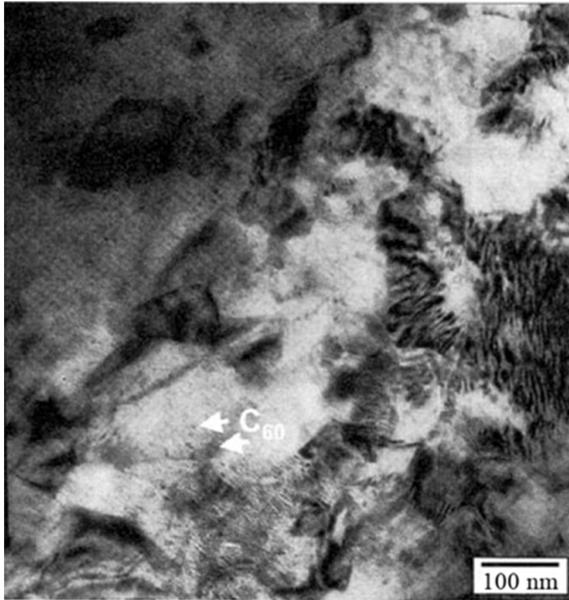


Figure 10: Materials mixing between fullerene/AZ31 (TEM image), reprinted with permission from Ref. [38].

while in service, it may result in premature failure of the component. Therefore, in order to obtain improved homogeneous mixing to form composite material, semipowder metallurgy (SPM) technique is found suitable in comparison to the conventional PM route [44–46]. The schematic of SPM is shown in Fig. 11, wherein the fullerene and metal powder were exposed separately to ethanol environment by employing mechanical agitator for an hour. This is to achieve homogenous dispersion of fullerene into the metal matrix. The aforementioned process is defined as

ultrasonication. The same ultrasonic process is continued for another half an hour after mixing fullerene into metal solution. Then, magnetic stirring is applied with vacuum distillation to extract the ethanol from the composite powder. The same powder is kept into oven under argon vacuum environment for 12 h [44–46]. The dried composite powder then pressed by hot press test machine for 2 h [44–46]. Argon environment is exploited to ensure oxidation-free material [44–46].

Performance of fullerene and fullerene-based nanocomposites

The lattice fringe observed from transmission electron microscopy (TEM) bright field micrograph evaluation indicates the presence of (002) *d* spacing of C₆₀ for fullerene nanocomposite. The similar observation also found in fullerene–rhodium nanocomposite. The TEM and X-ray diffraction (XRD) data confirm the presence of particles in nanometer scale for C₆₀ and Rhodium. Thus, aerosol decomposition method is a good candidate for the synthesis of nanocomposite materials [8]. The experiment conducted [9] for fabricated three different samples. Sample A is a fullerene-dispersed aluminum nanocomposite, Sample B is routed with stearic acid as an agent during the planetary ball milling process, and Sample C is routed with ethyl alcohol during the planetary ball milling process. The results show that the addition of agent significantly influences the hardness value and grain sizes. It is observed that hardness value increased for sample B then sample C and finally the in situ sample A. Besides, the grain size reduced for Sample B and Sample C (See Fig. 12). In general, the addition of stearic acid improved the hardness,

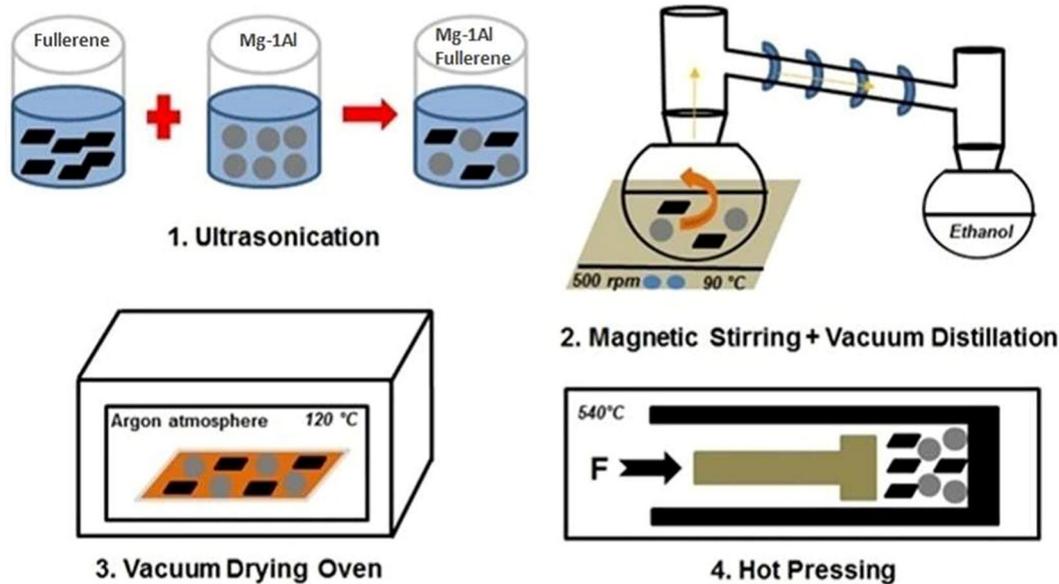


Figure 11: Schematic of SPM (reprinted with permission from Ref. [45]).

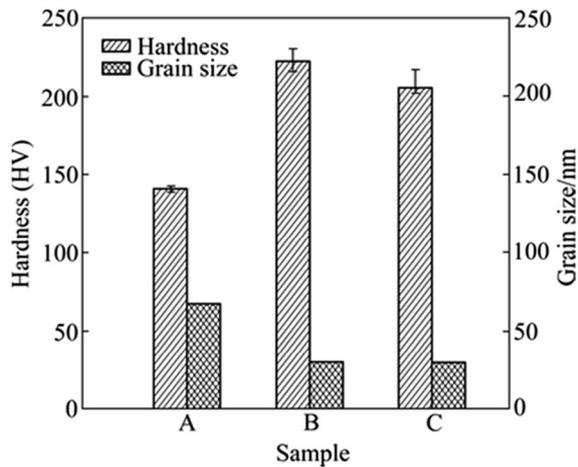


Figure 12: HV values of fullerene-based aluminum nanocomposites (reprinted with permission from Ref. [9]).

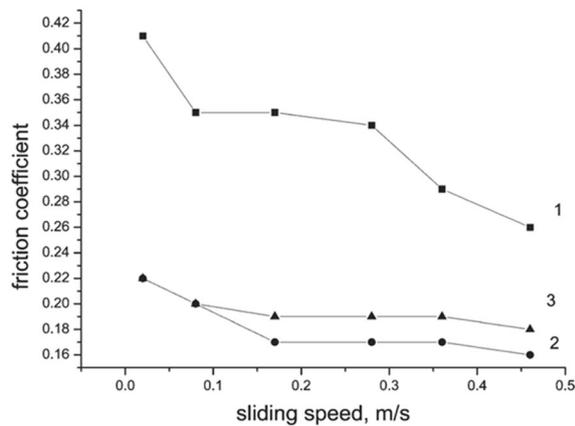


Figure 13: Frictional coefficient results (1) in situ PA6 (2) PA6/fullerene C60 composite (0.002 wt%) and (3) PA6/fullerene soot composite (0.1 wt%) [10].

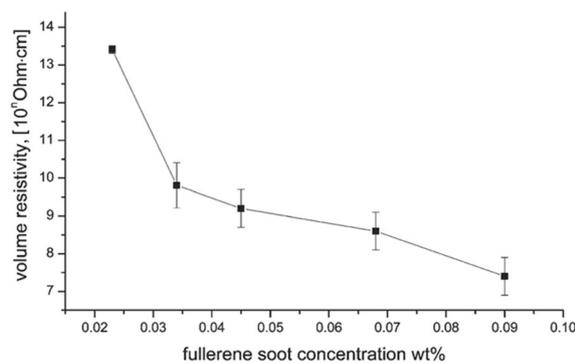


Figure 14: Volume resistivity vs concentration of fullerene Soot's [10].

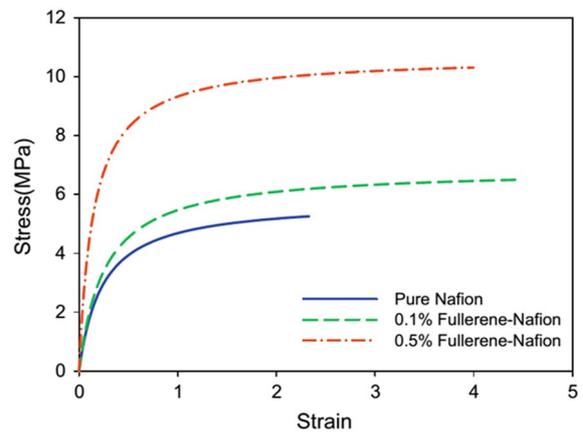


Figure 15: Stress–strain curve for pure Nafion, 0.1% fullerenes–Nafion, and 0.5% fullerenes–Nafion [12].

reduced the grain sizes, and thus improved the tribological properties of nanocomposites.

The frictional coefficient studies resulted in a 2-time reduction of coefficient of friction observed for composites infused with fullerenes fillers than in situ PA6. Furthermore, lowest coefficient of friction is observed for PA6/fullerene C60 composite (0.002 wt%) (See Fig. 13). The current voltage characteristics of the fabricated nanocomposites were evaluated and resulted a decrease in the resistivity in accordance with increase in fullerene soot concentrations (See Fig. 14) [10].

The mechanical properties of pure Nafion, 0.1% fullerenes–Nafion, and 0.5% fullerenes–Nafion were compared [12]. The results show that pure Nafion failed at lower stress value itself whereas 0.1% fullerenes–Nafion and 0.5% fullerenes–Nafion failed at higher stress values (Fig. 15). The fullerene–Nafion exhibited significant improvements in mechanical stiffness and strength [12]. The TEM results confirmed fine dispersion of fullerenes for milling process and the phase transformations to carbide and diamond phases are observed through XRD diffraction images (See Fig. 16). Furthermore, during sintering, the nanostructure is retained in Fe–fullerene composite C₆₀ [13].

The performance of fullerene-based nanocomposites fabricated by FSP is majorly measured with hardness variations in processed region and base materials. The dispersion of fullerene particles in base material greatly increases the hardness of processed zone. Morisada and Fuji [38] observed that the hardness of processed region by FSP of fullerene/AZ31 is approximately increased 3 times than the base material (i.e., AZ31)

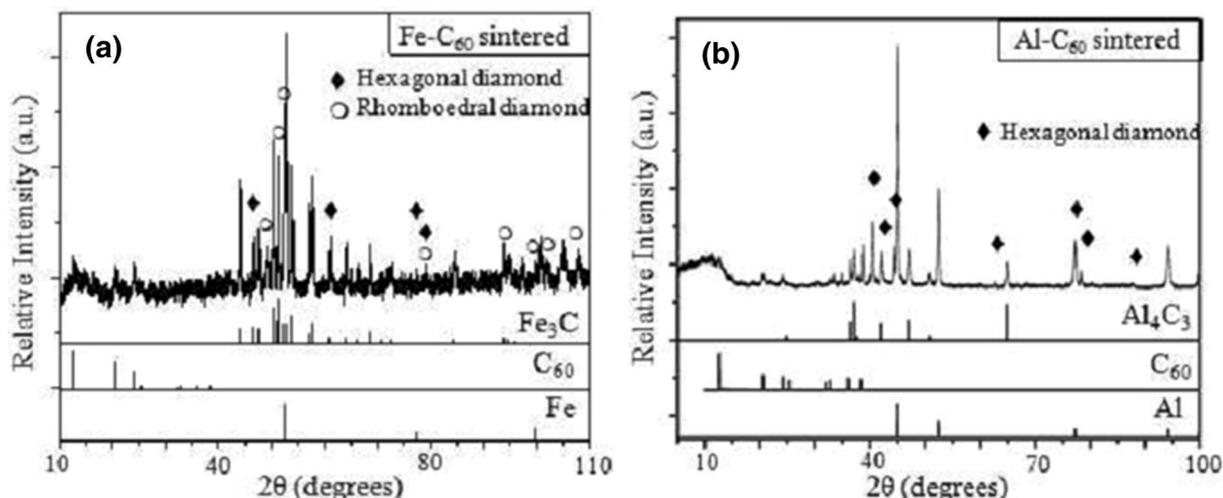


Figure 16: XRD diffraction images for Fe-C₆₀ and Al-C₆₀ [13].

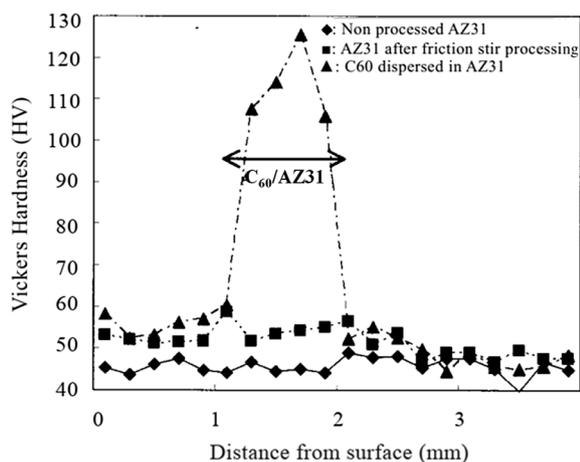


Figure 17: Hardness distribution of AZ31 processed by fullerene reinforcement FSP, normal FSP, and nonprocessed material (reprinted with permission from Ref. [38]).

hardness (see Fig. 17) due to uniform dispersion of fullerene C₆₀ and grain refinement. Similar increase in hardness (around two times higher than base material of AA5083) is observed in case of fullerene/AA5083 nanocomposites of FSP [37]. Higher fullerene concentration and uniform distribution of the same in matrix material increases the hardness of the processed zone due to particle reinforcement in matrix and reduction in grain size caused by strong stirring action.

Fullerene/magnesium composites fabricated by SPM process [44–46] showed limited work to identify the effect of fullerene quantity on the mechanical properties such as hardness and compression strength [44]. The effect of fullerene on the corrosion [44, 46] and wear properties [45] of the fullerene/magnesium composite was considered in the performance after

fabrication. Figure 18 shows that the dispersion of the fullerene is the function of the quantity. The agglomerate nature of the fullerene is reflected as the quantity of fullerene increases in the metal matrix composite (MMC). Interestingly, the effect of homogenous dispersion on to the mechanical properties is not seen significant. However, the hardness was increased with an increase in the fullerene quantity [44, 45] (see Fig. 19). The large surface area of fullerene lead to severe interfacial within the magnesium metal matrix. This is ultimately generating a diversified energy field within the pure material. Hence, dislocation movement through low angle and high angle grain boundaries was possibly presented due to continuous change in the atomic orientation while processing and dispersion of fullerene particles (in case of SPM process). This, in turn, promotes the higher dislocation density and restricted movement of dislocation within the composite material that led it to higher hardness within the processed region. Furthermore, the restriction of dislocation movement promotes its migration to all the possible direction that enhances the capacity to absorb the external energy applied on the composite, which in turn further increases the hardness of the material. However, the hardness slightly decreases when quantity of fullerene increases from 0.5 to 1%. This may be attributed to agglomerate nature of fullerene. As seen in Fig. 20, quantity of fullerene particle at some areas are higher that suggest the heterogeneous dispersion, which in turn may promote the deformation of composite material leading to reduction in the hardness. On the other hand, reduction in hardness can also be explained through the weak Vander walls bond and agglomeration of fullerene particle. Interestingly, the same author reported [44–46] two different hardness values of composite at 0.5% fullerene addition. The difference in the value is significant. The reason of such a large variation is not

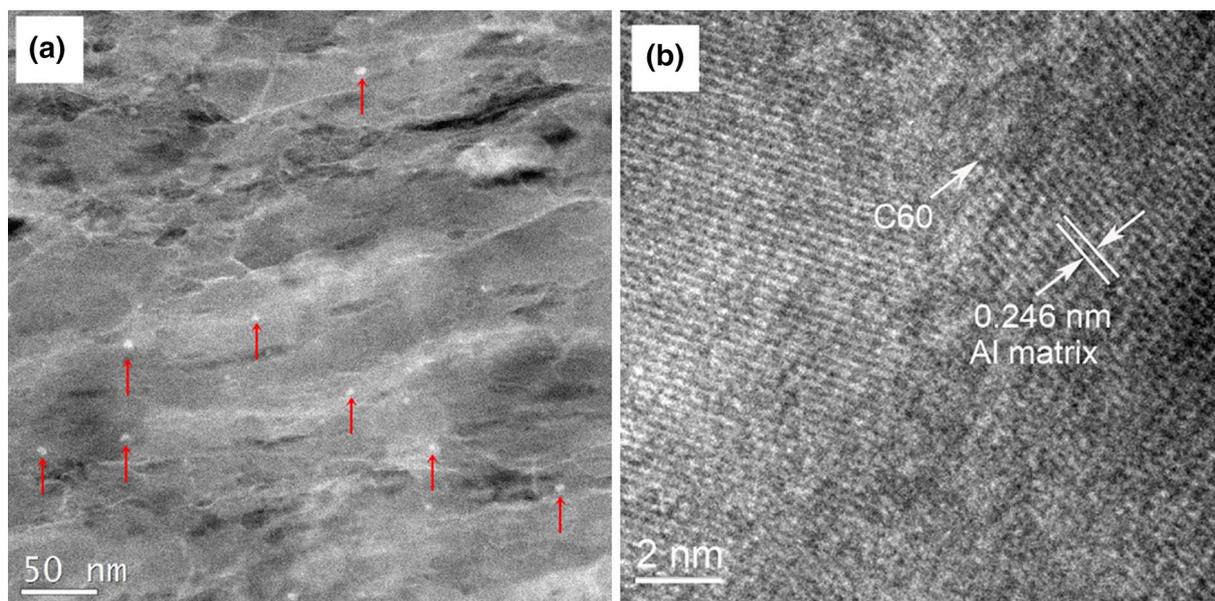


Figure 18: (a) HAADF TEM, (b) HRTEM images of HPT-processed Al/C₆₀ nanocomposite. The arrows show fullerene within the Al matrix [36].

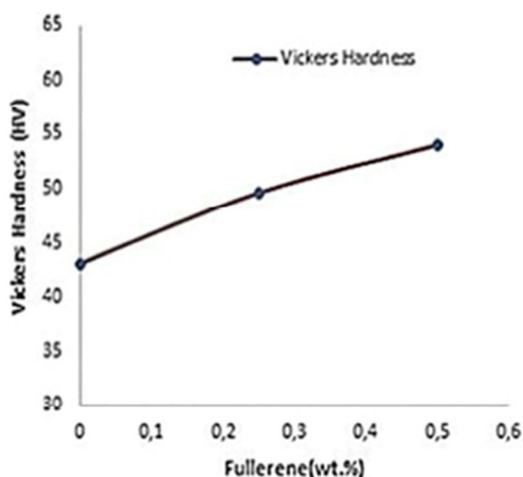


Figure 19: Hardness test results [44].

reported and cleared by the previous author even after similar manufacturing conditions. The same may be attributed to the size of specimen fabricated, i.e., 15 mm diameter and length [44, 45] compared to 25 mm diameter and 20 mm length [46]. The degree of fullerene dispersion is different with the size and it may affect the properties.

Apart from drastic variations in hardness, the fullerene-based composites fabricated by SPM process affect wear properties.

Wear rate of pure magnesium increases with an increase in the fullerene quantity till 0.5% fullerene addition [45]. On the other hand, rate of wear is slightly decreases in case of 1% fullerene added to Mg metal matrix. This is attributed to the aforementioned agglomerate nature of fullerene. In the mentioned case, variation in wear rate is not significant but it cannot be negligible at all. However, strong bond and large interfacial area due to lower density (i.e., after addition of fullerene into pure magnesium) resist the wear. Furthermore, corrosion resistance is decreased with addition to fullerene material. This is because of galvanic couple generated between fullerene rich and fullerene free grain boundaries. This, in turn, the site of energy diversification prone to corrosion. Hence, the study on homogenous dispersion of fullerene particle within metal matrix is vital as far as corrosion properties are concern. Similarly, compression strength of pure magnesium increased with an increase in the fullerene quantity at the time of fabrication. However, the experimental work is done only for 0.25% and 0.5% fullerene addition. The reported decrease in the density may be responsible for the higher compression strength [44]. Reduction in the density of fullerene material promotes the large interfacial area and therefore the load transfer from pure magnesium to hard fullerene can be absorbed through the adequate dislocation mechanisms. This subsequently results in high compressive strength. Table 1 shows the summary of reported material systems and methods for fabrications of fullerene-based nanocomposites.

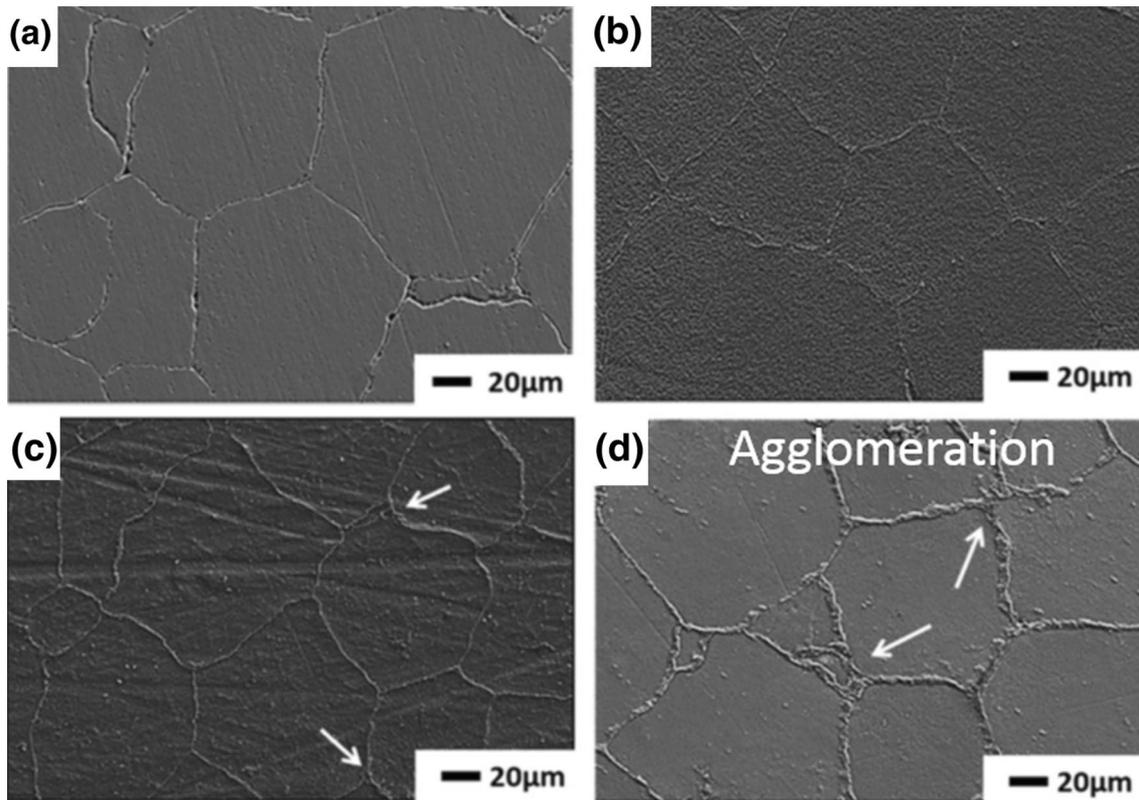


Figure 20: SEM micrographs of (a) Mg (b) Mg—0.25 wt% fullerene (c) Mg—0.50 wt% fullerene (d) Mg—1 wt% fullerene [45].

Conclusions

1. Addition of acidic agents in fullerene during the ball milling process and subsequent usage for fabrication of metal nanocomposite will influence the hardness and grain sizes in a greater manner.
2. Methods like powder metallurgy, RF sputtering and thin-film depositions are good candidates other than casting and steady-state process technologies.
3. The FSP composites based on fullerene compounds have a greater influence in increasing the hardness behaviors of the composite materials.
4. The fulleroid dispersion in PA6 shows significant reduction in coefficient of friction and also the electrical volume resistivity also found in decreasing mode as the fullerene soot concentration progresses. Also, reinforcement with certain polymers (e.g., Nafion) shows improvement in mechanical properties.

5. The milling and subsequent sintering unaltered the nanostructure specifically for Fe-C₆₀; this infers the milling and subsequent sintering can be a potential candidate for the process.

Future directives

- Adoptions of fullerenes in metal matrix composites are of greater impact in their tribological and electrical properties. Organic nanocomposites are supporting the electronic sector also. Thus, furthermore studies are to be kicked off for specific application with various environmental conditions.
- The material processing techniques are influencing the material properties for fullerene-based composites. Thus, rigorous studies are required to know the synergy between the process parameters and properties.

TABLE 1: Summary of various reported materials system based on fullerene nanocomposites.

Period	Composite system	Techniques used	Researchers
1993	Fullerene–rhodium nanocomposites	Aerosol Decomposition	Abhijit S. Gurav, Zhibang Duan, Lumin Wang, Mark J. Hampden-Smith, and Toivo T. Kodas [8]
1995	Fullerene-reinforced aluminum	Powder metallurgy and casting	E. V. Barrera, J. Sims, and D. L. Callahan [47]
1997	Fullerene composite	Liquid chromatography, pulverizing, compression molding	Shunichiro Tanaka [48]
1999	Metal-fullerene	Mechanical alloying-Ball Milling	Umemoto, Minoru, ZhiGuang Liu, K. Masuyama, and Koichi Tsuchiya [49]
2004	Hollow fullerene-like Nanoparticles as solid lubricants In composite metal matrices	Using foaming agents and compaction, impregnation	Reshef Tenne Rehovot (IL), Rapoport, Lod (IL); Mark Lvovsky, Herzliya (IL), Yishay Feldman, Ashdod (IL); Volf Leshchinsky, Rishon Letzion (IL) [50]
2006	C60/AZ31 nanocomposite	Friction Stir Processing	Y. Morisada, H. Fujii, T. Nagaoka and M. Fukusumi [38]
2007	Fullerene/A5083 composites	Friction Stir Processing	Y. Morisada, H. Fujii, T. Nagaoka, K. Nogi, M. Fukusumi [37]
2008	Mixing of metals and polymers with fullerenes Nanofibers	Electromagnetic field-induced and acoustic mixing	Enrique V. Barrera, Yildiz Bayazitoglu [52]
2010	Electro-active nanocomposite actuator based on fullerene-reinforced Nafion	Solvent recasting method	Jung-Hwan Jung, Sridhar Vadahanambi, Il-Kwon Oh [12]
2010	Al or Fe Matrix reinforced with fullerene	Spark plasma sintering, mechanical alloying	Francisco C. Robles, H. A. Calderon [51]
2011	Composites of Fe–C ₆₀ and Al C ₆₀	Mechanical milling and spark plasma sintering	I. I. Santana, F. C. Robles Hernandez, V. Garibay Febles and H. A. Calderon [13]
2014	Aluminum-based nanocomposite reinforced with fullerenes	Ball milling technique	Kwangmin CHOI, Jiyeon SEO, Donghyun BAE, Hyunjoo CHOI [9]
2017	Fullerene-reinforced aluminum matrix Nanocomposites	High-energy mechanical milling and hot extrusion or high-pressure torsion (HPT)	Hamed Asgharzadeh, Hamid Faraghi, Hyoung Seop Kim [36]
2018	TiC–AlC—and FeC with inclusions of the C ₆₀	High voltage electric discharge (HVED) treatment	O. Sizonenko, S. Prokhorenko, R. Wojnarowska-Nowak, J. Polit, A. Torpakov, D. Zak, and E. M. Sheregii [35]
2018	Fullerene-reinforced magnesium matrix composites fabricated	Semipowder metallurgy	Muhammet Emre Turan, Yavuz Sun, Yasin Akgul [44]

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