Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 97 (2014) 1033 – 1040
Procedia Engineering
www.elsevier.com/locate/procedia

12th GLOBAL CONGRESS ON MANUFACTURING AND MANAGEMENT, GCMM 2014

Graphene Reinforced Metal Matrix Composite (GRMMC): A Review

Prashantha Kumar H.G[a,]*, M. Anthony Xavior[b]

[a]*Junior research fellow, School for mechanical building sciences, VIT University, Vellore –632014, INDIA*
[b] *Professor, School for mechanical building sciences, VIT University, Vellore –632014, INDIA*

Abstract

Graphene has remarkable mechanical properties, which makes it hypothetically a good reinforcement in metal composites. It also has exclusive optical and thermal properties, which make it striking filler for producing multifunctional composites especially in case of metal matrix composite due to its viability and outstanding mechanical properties. In the past few years, relatively little consideration has been given on graphene reinforced metal matrix composite (GRMMC) in comparison to polymer and ceramic matrix composites. This review article gives a wide-ranging overview on the state of the dispersion of graphene in composites, including materials already synthesized and characterization. This paper also focus on different dispersion methods, mechanism of strengthening, composites synthesized using graphene and its applications.

Selection and peer-review under responsibility of the Organizing Committee of GCMM 2014

Keywords: Graphene; Dispersion; Composite

1. Introduction

Graphene is one atomic layer thick sheet of carbon or film of carbon atoms. Due to their sp^2- hybridized two dimensional honeycomb structure, low weight, thermal, electrical and mechanical properties, it has been attracted to worldwide. In fact, graphene has a number of unique properties, which makes future applications and it’s also the strongest material ever measured; it's the stiffest material; it's the most stretchable crystal and most thermally conductive material known to man [1-4]. Scientists had speculated about graphene for decades before, it was productively synthesized in the lab during 2004 by A. K. Geim and K. S. Novoselov [5].

* *Corresponding author. Tel.: +91 9742527629*
E-mail address: prashanthakumar.hg@vit.ac.in

Selection and peer-review under responsibility of the Organizing Committee of GCMM 2014
doi:10.1016/j.proeng.2014.12.381

Graphene nanoplatelets (GNPs) consist of small stacks of graphene that can replace carbon nanotubes because it possesses all the properties compared to CNTs. The main advantages of using graphene over CNTs are a higher specific surface area[6] and less tendency to twist, which makes it easier to disperse into a matrix,[7] simultaneously improving mechanical properties in terms of strength and stiffness. It is also relatively relaxed to produce, inexpensive and potentially has not much health hazards compared to other allotropes of Carbon [8]. The intrinsic properties of Graphene nanoplatelets (GNPs) have found to be myriad applications and are useful as nanoscale additives for innovative composites, as a component in advanced batteries and ultra/super capacitors, as the conductive component in subject to coatings or adhesives, and as a component of e-inks. The research of graphene including the control of the graphene films on substrates, functionalizing graphene, as reinforcement and exploring the applications of graphene has grown exponentially as shown in Fig. 1. According to *Web of Science* database, there were 164 papers published in 2004 with the word "graphene" in their titles, abstracts or list of keywords. By 2010, there were 3,671 such articles recorded to the Source *Thomson Reuters Web of Knowledge.* However with this substantial advantages need to be reinforcing to the material which are especially in application with aeronautical, aerospace and automobile industries. However it's hard to achieve improved mechanical performances using alloy components modification, deformation and heat treatment processes. Matrix with (C, Al_20_3, SiC, B_4C and CNTs) reinforcement's composites is roughly investigated [9-12]. Now the biggest challenges is to develop the equivalently graphene dispersion strengthened composite without damaging the intrinsic structures. GNFs/Metal Matrix nanocomposites may be favourable candidate for the next age group nanocomposites. Some of the important mechanical and physical properties of graphene are summarized in the Table no.1.

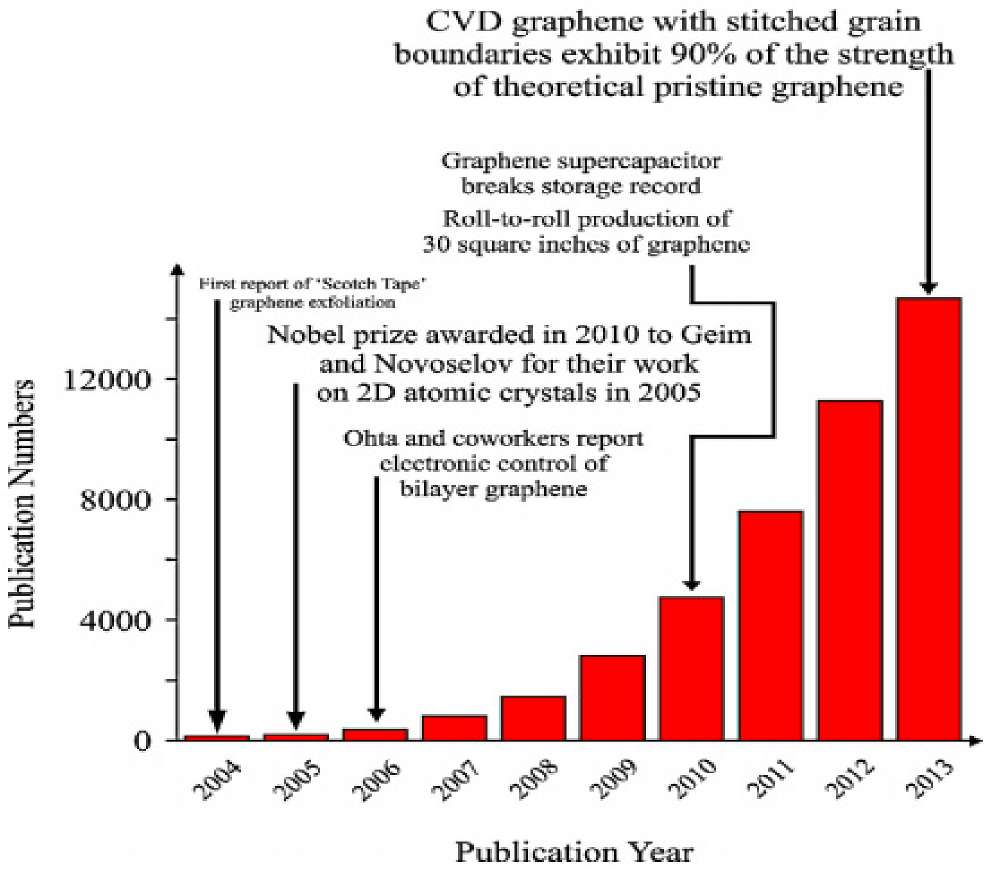

Fig.1 Graphene publication time line in past years [13]

Table .1 Important Physical and Mechanical Properties of Graphene

Property	Graphene	Ref
Electron mobility	1500 $cm^2\ V^{-1}\ s^{-1}$	[14]
Resistivity	$10^{-6}\Omega$-cm	[14]
Thermal conductivity	$5.3 \times 10^3\ Wm^{-1}K^{-1}$	[14]
Transmittance	>95% for 2nm thick film >70% for 10nm thick film	[15]
Elastic modulus	0.5 – 1 Tpa	[15]
Coefficient of thermal expansion	-6×10^{-4}/K	[15]
Elastic modulus	0.5 – 1 Tpa	[15]
Specific Surface area	2630$m^2\ g^{-1}$	[16]
Tensile strength	130 GPa	[16]

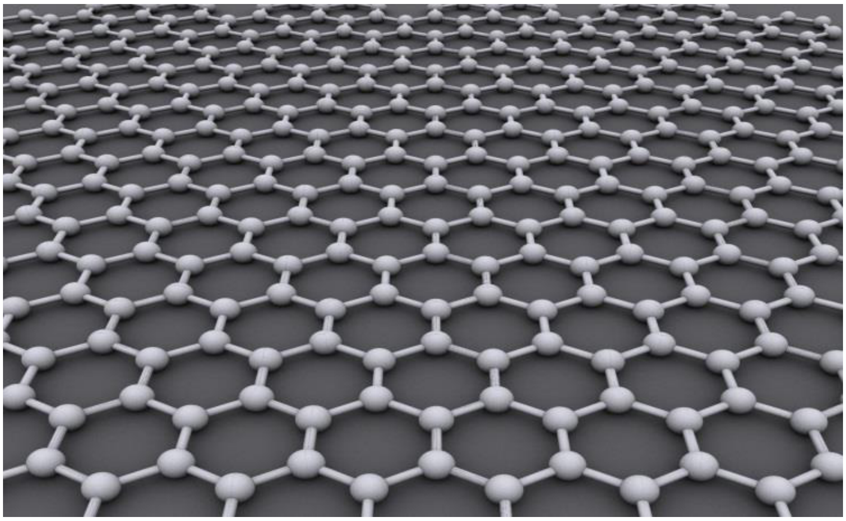

Fig.2 A molecular model of single atomic layer graphene

2. Graphene

The explanation of graphene covers all forms of graphitic material from 100 nm <thick platelets down to single layer graphene [17].However, the obtainability of single-or few-layer graphene that has caused the interest. In fact, it is possible to distinguish between flakes of graphene with different numbers of atomic layers in a transmission optical microscope due to its nature of significant optically energetic[18]. The work to determine the number of layers to be used for the reinforcement was formed and found that monolayer has the higher stress transfer than the bilayer graphene [19] and the flakes are sufficiently large(>30 micro meter) and aspect ratio should be high for the effective reinforcement of both bilayer[20] and monolayer graphene in the composite[21]. There has already been considerable effort put into the development of way of preparing high-quality graphene in large quantities for the research purposes and also with the view to possible applications where it is suitable [22]. The very first attempt given to graphene preparation is break the graphite down into graphene by techniques known as a mechanical cleavage or liquid phase exfoliation. The other method chemical vapour deposition (CVD) is also used to synthesize graphene and in recent days thinner forms of graphite nanoplatelets (GNPs)[23] by different techniques known to be acid irradiation of graphite to microwave radiations, ball milling and ultrasonication. Fig.2 shows a molecular model of single atomic layer graphene sheet.

3. Metal-Graphene composites

There are number of motives to develop graphene-metal composites. The strengthening mechanism of graphene reinforcement is thought to be related to the excellent mechanical and the unique structured characteristics of graphene, and good bonding interfaces between graphene and matrix. There are many challenges involved to get graphene dispersed metal matrix composite with the existing conventional metallurgical process or methods due to huge density difference between GNFs and metal matrix, more interfacial contact area than carbon nanotubes and also reaction at matrix reinforcement interface[24] because metals are much reactive. The work relating to this field is still remaining in their infancy. But the increase of publications in this category signifies that growing an interest towards graphene based metal composites.

Both graphene oxide (GO) and graphene nanoplatelets (GNPs) are considered in some of research work. The dispersion of GNFs into matrix were presently took place by Chemical mixing, Mechanical mixing and electrode deposition method. In the first category route Mg-1%A-1%Sn alloy reinforced with low content of graphene sheets (GNFs) with ethanol solvent using mechanical agitator at the same time separately ultra-sonication of GNFs[25] and Al-GNPs with acetone same process followed and as shown in Fig.3.(a) uniform dispersion[26].The X-ray mapping as shown in Fig 3.(b) is used to confirm the dispersion of GNPs in the composites. Next category Cu-Gr composites by electrodeposition method will enhance the mechanical and retaining the electrical properties [27] a nickel sulfamate solution, and 1 g/L GO nanosheets in suspension, were used to harvest graphene/Ni composites. Electrodeposition solution was agitated by magnetic stirring, which could propel GO nanosheets and nickel ions onto the cathode surface, as well as prevent the nanosheets sinking. The temperature was maintained at 55° C by an automatic heat control unit and fig.3(c) shows the SEM image of Ni/Graphene. In addition electro deposition process being a low temperature process which preserves the properties of Gr/Go during the preparation of composite is scalable and cost effective process. In case of exploiting method carried out by exploiting the GO into several layers of nanosheets in deionized water fallowed by ball milling[28]. Feeding the GNFs into melt of Mg at 700° C and ultrasonicated with amplitude of 60 micro meter of 15 min long in case of Mg-Gr composite[29]. Ultrasonic processing is considered as ultimate for processing of GNFs in liquid molten state but SEM image Fig 3.(d) shows failure in dispersion of thin sheets in molten metal. At last by blending, milling in a Zoz high energy attritor under argon atmosphere with stearic acid to prevent the agglomeration in case of Al-0.1%Gr, along with milling cycles which imparts the some degree of refinement providing clean metallurgical interface [30, 31], but during milling graphene may adhere to the Al particle and reaction may occur during subsequent ie sintering and extrusion stages. Further solvent exchange method enables to preparation of stable dispersion of Gr from N-Methyl-2-Pyrroliodone (NMP) in low melting point of ethanol and it will very useful in preparation of composites and Gr based materials and dispersed solution can be keep for the long days[32].

With the excellent tensile strength (130Gpa) and toughness (0.5-1TPa) of graphene (Table.1) make it as an efficient reinforcement to strengthen and stiffen the metal. The uniform distribution of second phase will constitutes the even properties along the composite and effective load transfers from matrix to reinforcement take place when there is good interfacial connection between them. The powder metallurgy is one of the popular solid state methods used in production of metal matrix composite, in the same way effective means to produce graphene based metal matrix. In semi powder metallurgy method the materials are bended and mixed by any of means above discussed and compressed in mould. Sintering is a heat treatment process performed on the compacted samples to bond its metallic particle thereby increasing strength and hardness. Graphene concentration and sintering environments have a significant effect on mechanical properties. It is clear from mass differences, the density of matrix composite decreases with addition of GNPs. But Al- graphene combinations the measured experimental densities of both pure Al and composite are amazingly greater than theoretical densities due to Oxidation of Al leads to formation of high density aluminium oxide during the sintering process [26]. Due to the significant coefficient of thermal expansion mismatch between the graphene and the matrix materials result in prismatic hitting of dislocations at the boundaries, prominent to strengthening of the composite matrix. Dislocations density depends on range of reinforcement particle. Greater the dislocation density which results in increased in strength of the composite[25].

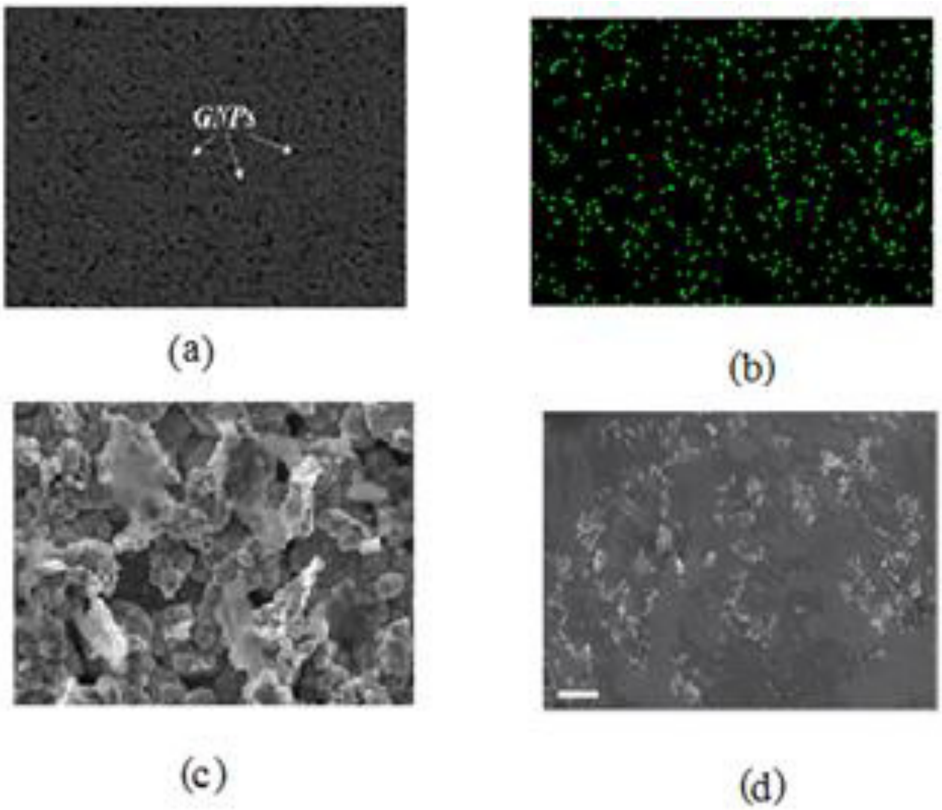

Fig.3(a) SEM image of Al/0.3 wt% uniformly GNPs dispersed composite, **(b)** X-ray mapping of Mg–Al–Sn–GNPs Composite, **(c)** SEM Image of graphene/Ni composites, **(d)** SEM Image showing failure of Gr Dispersion in Mg molten Ref [26], [27], [28],[29] respectively

The extreme improvement in the ultimate tensile strength of low percentage GNPs reinforced Al and Mg composite of any other reinforcement processed by compaction and extrusion. During hot extrusion most of the GNFs try to align along the tensile direction (in plane) and this enables to attain in plane strength, acts as constraint to dislocation propagation. Also from the Table.2 demonstrate that the graphene nanoplatelets are ready to participate in hybrid composite to enhancing the ultimate tensile strength properties. From the graphene reinforced composites updated summery, (Table.3) the application mainly are in the electrical and biomedical fields. Some of aluminium based composite are prepared but lot of work is to be done on Al-graphene composite for real time automobile applications.

Table.2 Ultimate tensile strength for low percent of GNFs

Material	UTS (Mpa)	Ref
Al/0.3 Wt.% GNPs(Composite)	280(170 without GNPs)	[26]
Mg-1Al-1Sn-0.18GNPs (Composite)	208(161 without GNPs)	[25]
GNPs 0.5–Ni/Cu (Hybrid Composite)	271(230Without GNPs)	[33]

UTS: Ultimate tensile strength.

Table.3 A site view on graphene reinforced composite

Composition	Properties and applications	Ref
Pt-Graphene	Super capacitor- fuel cell applications	[34]
	Electrochemically active surface area-Catalyst carrier in electrocatalysis and fuel cells applications	[35]
Al/Pd/Pt	Acts as catalytic methanol oxidation-Methanol fuel cell applications	[36]
Au-graphene	DNA gets adsorbed faster than only Au surface Biosensors, Biodevices and DNA Sequencing applications	[37]
	Voltammograms of electrolytic reduction of oxygen and glucose oxidation shows more Au- Graphene than alone Au- Fuel cell and bioelectroanalytical chemistry applications	
	Apparent electrode area Environmental monitoring – detection of mercury	[38]
	Electroactive surface area- electrochemical detection of DNA specific sequence applications	
		[39]
Co-Graphene	Anode material for Li-ion battery applications	[40]
Si-Graphene	Anode material for Li-ion battery applications	[41]
Al powder-graphene	Graphene as reinforce -Strengthening of Composite applications	[30]
	Decreased strength and hardness	[26]
	Lower failure strain and higher Vickers hardness	[30]
Mg-Graphene based composite	Production of Ultra high performance metal matrix composite	[29]
Cu-graphene composite foil	Higher the electrical conductivity and hardness compare to copper alone	[27]
Mg-1%A-1%Sn reinforced graphene	Superior Nano-filler adhesion and increased and tensile strength	[25]
Au-Graphene-HRP - CS	H_2O_2 Biosensor applications	[42]

4.Summary and conclusions

It is worth to note that the notable benefit of the GNFs/Metal matrix nanocomposites, comparing with conventional metal matrix composites, and has an immense potential to fabricate the composite reinforce with Graphene having important properties and have high levels of stiffness and strength, this means that the outcome of composite will possess outstanding mechanical properties. Although some positive results have been achieved, there still have a lot of unknown influencing issues need to be explore in graphene reinforced metal matrix nanocomposites and the future research will be focused on the optimization of processing parameters to improve the content and dispersion of GNFs in the metal matrix, also sintering and extrusion parameters.

References

[1] Lee C, Wei XD, Kysar J W, Hone J. Measurement of the elastic properties and intrinsic strength of monolayer Graphene. Science 2008; 321:385-388.

[2] Georgiou T, Britnell L, Blake P, Gorbachev RV, Gholinia A, Geim AK, et al. Graphene bubbles with Controllable curvature. Appl Phys Lett 2011; 99:093103-093103.

[3] Novoselov K S, Geim A K, Morozov S V, Jiang D, Zhang Y, Dubonos S V, et al. Electric field effect in atomically thin carbon films. Science 2004; 306:666-9.

[4] Balandin AA. Thermal properties of graphene and nanostructured carbon materials. Nat Mater 2011; 10:569-81.

[5] A. K. Geim & K. S. Novoselov Nature Materials, Vol 6 183 - 191 (2007).

[6] Y. C. Fan, L. J. Wang, J. L. Li, J. Q. Li, S. K. Sun, F. Chen, L. D. Chen and W. Jiang: Carbon, 2010, 48, (6), 1743–1749.

[7] J. Wang, J. J. Zhu and W. Jiang: Mater. Trans., 2009, 50, (4), 749–751.

[8] C. W. Lam, J. T. James, R. McCluskey, S. Arepalli and R. L. Hunter: Crit. Rev. Toxicol., 2006, 36, (3), 189-217

[9] Song M, He YH, Fang SF. Yield stress of SiC reinforced aluminum alloy composites. J Mater Sci 2010; 45:4097-110.

[10]Pierard N, Fonseca A, Colomer J F, Bossuot C, Benoit JM. Ball milling effect on the structure of single-wall Carbon nanotubes. Carbon 2004; 42:1691-1697.

[11]Sun C, Song M, Wang Z W, He Y H. Effect of particle size on the microstructures and mechanical properties of SiC-reinforced pure aluminium composites. J Mater Eng Perform 2011; 20(9):1606-1612.

[12]Topcu I, Gulsoy HO, Kadioglu N, Gulluoglu AN. Processing and mechanical properties of B4C reinforced Al matrix composites. J Alloys and Compd 2009; 482:516-521.

[13]E.P. Randviir, et al., Mater. Today (2013), Volume 48, Issue 8, July 2010.

[14]Wonbong ChoiIndranil Lahiri Raghunandan Seelaboyina Critical Reviews in Solid State and Material Sciences. 01/2010; 35(1):52-7.

[15]Caterina Soldano, Ather Mahmood, Erik Dujardin CEMES Volume 48, Issue 8, July 2010, Pages 2127–2150.

[17]Jang BZ, Zhamu A. Processing of nanographene platelets (NGPs) and NGP nanocomposites: a review. J Mater Sci 2008; 43:5092–101.

[18]Blake P, Hill E W, Castro Neto A H, Novoselov K S, Jiang D, Yang R, et al. Making graphene visible. Appl Phys Lett 2007; 91:063124.

[19]Gong L, Young R J, Kinloch I A, Riaz I, Jalil R, Novoselov K S. Optimizing the reinforcement of polymer-based nanocomposites by graphene. ACS Nano 2012; 6:2086–95.

[20]Frank O, Bouša M, Riaz I, Jalil R, Novoselov KS, Tsoukleri G, et al. Phonon and structural changes in deformed bernal stacked bilayer graphene. Lett 2012; 12:687–93.

[21]Hernandez Y, Nicolosi V, Lotya M, Blighe FM, Sun ZY, De S, et al. High-yield production of graphene by liquid-phase exfoliation of graphite. Nat Nanotechnol 2008; 3:563–8.

[22]Rao CNR, Biswas K, Subrahmanyam KS, Govindaraj.A. Graphene, the new carbon. J Mater Chem 2009; 19:2457–69.

[23]Jang B Z, Zhamu A. Processing of nanographene platelets (NGPs) and NGP nanocomposites: a review. J Mater Sci 2008; 43:5092–101.

[24]Young R J, Kinloch I A. Graphene composites, In: Nicolais L, Borzacchiello A, Lee SM, editors. Wiley Encyclopaedia of Composites 2011.

[25]Muhammad Rashada, Fusheng Pan, Muhammad Asif, Aitao Tang, Journal of Industrial and Engineering Chemistry JIEC-1870; No. of Pages 6.

[26]Stephen F. Bartoluccia, Joseph Parasa, Mohammad A. Rafieeb, Javad Rafieec, Sabrina Leea, Deepak Kapoora, Nikhil Koratkarc Graphene–aluminum nanocomposites Materials Science and Engineering A 528 (2011) 7933–7937.

[27]Chokkakula L. P. Pavithra, Bulusu V. Sarada1, Koteswararao V. Rajulapati, Tata N. Rao1 & G. Sundararajan A New Electrochemical Approach for the Synthesis of Copper-Graphene Nanocomposite Foils with High Hardness scientific reports 4 : 4049 DOI: 10.1038/srep04049.

[28]Jingyue Wang, ZhiqiangLi, GenlianFan, HuanhuanPan, ZhixinChen and Di Zhanga, Reinforcement with

graphene nanosheets in aluminium matrix composites Scripta Materialia 66 (2012) 594–597.
[29]Lian-Yi Chen , Hiromi Konishi, Axel Fehrenbacher, Chao Ma, aJia-QuanXu, Hongseok Choi,Hui-Fang Xu, Frank E. Pfefferkorna and Xiao-Chun Li, Novel nano processing route for bulk graphene nanoplatelets reinforced metal matrix nanocomposites Scripta Materialia 67 (2012) 29–32.
[30]Ebinezar, Bheemraokamble, Analysis of hardness test for aluminium carbon nanotube metal matrix and graphene, Indian journal of Engineering, volume10, Number 21, April 2, 2014.
[31]R. Perez-Bustamante, D. Bolanos-Morales, J. Bonilla-Martínezb, I. Estrada-Guela, R. Martínez-Sanchez Microstructural and hardness behaviour of graphene-nanoplatelets/aluminium composites synthesized by mechanical alloying WO 2011105530-A1; 2011.
[32]Xiaoyan Zhang, Anthony C. Coleman, Nathalie Katsonis, Wesley R. Browne, Bart J. van Wees and Ben L. Feringa Dispersion of graphene in ethanol using a simple solvent exchange Method 20th July 2010, Accepted 23rd August 2010 DOI: 10.1039/c0cc02688c.
[33]YanxiaTanga, XiaominYang, Rongrong Wang, MaoxinLi Enhancement of the mechanical properties of Graphene–copper composites with graphene–nickel hybrids Materials Science & Engineering A599 (2014)247–254
[34]Samulki, E T 2008. Exfoliated graphene separated by platinum nanoparticle. Chem. Mater.20; 6792-6797
[35]Yueming Li, Longhua Tang, Jinghong Li Preparation and electrochemical performance for methanol oxidation of pt/graphene nanocomposites volume 11. Issue 4, April 2009, pages 846-849**.**
[36]C Xu, X Wang, J Zhu - The Journal of Physical Chemistry C, 2008 - ACS Publications Graphene−Metal Particle Nanocomposites *J. Phys. Chem. C*, 2008, *112* (50), pp. 19841–19845.
[37]Song B, Li D, Qi W, Elstner M, Fan C, Fang H. Graphene on Au (111): a highly conductive material with excellent adsorption properties for high-resolution bio/nano detection and identification. Chemphyschem. 2010 Feb 22; 11(3):585-9.
[38]Jingming Gong, Ting Zhou, Dandan Song, Lizhi Zhang Mono dispersed Au nanoparticles decorated graphene as an enhanced sensing platform for ultrasensitive stripping voltammetric detection of mercury(II), Volume 150 ,Issue2, 28 October 2010, Pages 491-49.
[39]Meng Du, Tao Yang and Kui Jiao Immobilization-free direct electrochemical detection for DNA specific sequences based on electrochemically converted gold nanoparticles/graphene composite film J. Mater. Chem**,** 2010, 20, 9253-9260.
[40]Shubin Yang Dr, Guanglei Cui Dr, Shuping Pang, Qian Cao, Ute Kolb Dr, Xinliang Feng Dr, Joachim Maier and Klaus Mullen Pro, Volume 3, Issue 2, pages 236–239, February 22, 201.
[41]Chou, S, Wang, J, Choucair, M, Liu, HK, Stride, JA & Dou, SX (2010), Enhanced reversible lithium storage in a nanosize silicon/graphene composite, Electrochemistry Communications, 12(2), pp. 303-306.
[42]Kangfu Zhou, Yihua Zhu Xiaoling Yang, Jie Luo, Chunzhong Li, Shaorong Luan A novel hydrogen peroxide biosensor based on Au–graphene–HRP–chitosan biocomposites Volume 55, Issue 9 30 March 2010, pages 3055-3060.