EFFECT OF GRAPHENE ON MECHANICAL PROPERTIES AND FLAME RETARDANCY OF POLYCARBONATE/ ACRYLONITRILE BUTADIENE STYRENE NANOCOMPOSITES

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A dissertation submitted in fulfillment of the requirements for the award of the degree of Master of Science (Polymer Technology)

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2014

To my beloved parents and sister

First and foremost, I would like to acknowledge my supervisor, Prof. Dr. Azman Bin Hassan, for his encouragement, guidance and inspiration throughout this research.

I wish to express my deep appreciation to all the lecturers from Department of Polymer Engineering who have directly or indirectly contributed towards the success of my research project. I also wish to thanks all the technicians of laboratories of polymer engineering for their help in my research.

Most importantly, I would like to extend my sincere thanks to my family for their continuous love and encouragement, for always believing in me and never failing to provide me any support.

ABSTRAK

Polikarbonat/akrilonitril butadiena stirena (PC/ABS) komposit nano yang mengandungi platelet nano grafin (GNPs) dan bisfenol A bis (difenil fosfat) (BDP) telah berjaya dihasilkan dengan menggunakan penyemperit skru berkembar berlawanan arah dan diikuti dengan pengacuan suntikan. Di dalam kajian ini BDP telah digunakan sebagai bahan perencat api. Sifat-sifat mekanikal komposit nano telah dikaji melalui ujian tegangan, lenturan dan hentaman. Termogravimetri analisis (TGA) digunakan untuk menilai sifat-sifat terma komposit nano, dan morfologi komposit nano diperhatikan melalui imbasan elektron mikroskop (FESEM). Struktur kimia komposit nano PC/ABS telah diuji melalui fourier infra merah (FTIR). Kebolehbakaran komposit nano telah diukur dengan menggunakan indeks penghad oksigen (LOI) dan UL94. Sifat-sifat mekanikal adunan PC/ABS meningkat apabila GNPs dan BDP digabungkan. 3wt.% kandungan GNPs memberikan nilai maksimum bagi kekuatan sifat regangan, modulus Young dan sifat kebolehlenturan bagi komposit nano. Analisis TGA mendedahkan kestabilan terma PC/ABS/BDP dan komposit nano telah meningkat dengan ketara berbanding dengan yang PC/ABS. Ini dapat dilihat apabila 1wt.% GPNs digunakan 20% suhu kehilangan berat (T20) meningkat sebanyak 23 °C. Baki hasil pembakaran PC/ABS/GNPs3 meningkat secara dramatik sebanyak 64 % apabila 10 wt.% BDP ditambah. Sinergi dalam LOI dan UL94 telah diperhatikan untuk PC/ABS/GNPs3/BDP10 dibandingkan dengan PC/ABS/BDP. GNPs telah tersebar dengan baik didalam adunan PC/ABS seperti didedahkan oleh FESEM. Interkalasi GNPs turut diperhatikan apabila BDP ditambah kepada komposit nano. Spektrum FTIR menunjukkan bahawa penambahan GNPs ke dalam PC/ABS matriks tidak membawa apa-apa perubahan ketara dalam struktur kimia. Walau bagaimanapun beberapa interaksi ikatan hidrogen antara GNPs dan campuran PC/ABS dicadangkan.

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LIST OF ABBREVIATION

ABS	-	Acrylonitrile-butadiene-styrene
ASTM	-	American standard testing methods
BDP	-	Bisphenol A bis(diphenyl phosphate)Safety
BEP	-	Bisphenol A bis(diethyl phosphate)
CNT	-	Carbon nanotube
CO_2	-	Carbon dioxide
DSC	-	Differential scanning calorimetry
EVA	-	Ethylene-vinyl acetate
FESEM	-	Field emission scanning electron microscopy
FTIR	-	Fourier transform infrared
GNPs	-	Graphene nanoplatelets
HRR	-	Heat release rate
LOI	-	Limiting oxygen index
Mw	-	Molecular weight
N_2	-	Nitrogen
O_2	-	Oxygen
PA6	-	Polyamide 6
PC	-	Polycarbonate
PDMS	-	Poly dimethylsiloxane
PEN	-	Poly(ethylene-2,6-naphthalate)
Phr	-	Parts per hundred
PHRR	-	Peak heat release rate
PLA	-	Poly(lactic acid)
PLS	-	Polymer/layered silicate
PMMA	-	Poly methyl methacrylate
PP	-	Poly(propylene)
PS	-	Poly(styrene)

PVA	-	Poly(vinyl alcohol)
PVC	-	Poly(vinyl chloride)
RDP	-	Resorcinol bis(diphenyl phosphate)
SWCNT	-	Single wall carbon nanotube
t_{ign}	-	Ignition time
TGA	-	Thermogravimetric analysis
TPP	-	Triphenyl phosphate
UL 94	-	Universal laboratory burning champer
VST	-	Vicat softening temperature
wt. %	-	Weight percentage
xGnP	-	Exfoliated graphene nanoplatelets
XRD	-	X-ray diffraction

LIST OF SYMBOLS

Å	-	Angstrom
	-	Diffraction angle (°)
λ	−	X-ray wavelength (Å)
μm	-	Micrometer

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Recently polymeric materials are structured by "on-demand properties". They are also performance through the blending a kind of polymer with the other polymers, additives or fillers. The ability to combine the existing polymer into new composites with commercialize properties, that offers the advantage of reducing the research and development cost compared to the development of new monomer and synthesize modern polymer to yield a comparable property configuration. Polymer blending has been accepted as a significant technique to make new and valuable polymeric products. The resulting material may obligate properties superior toward the components by blending polymers. However it can be attractive to industry as much less costly and time saving approach to meet the need for high performance material than would be the synthesis and development of an entirely.

One of the engineering thermoplastics with the widely used in a variety of high performance application is polycarbonate (PC). It is a kind of ductile thermoplastic compare to the other polymers such as nylon, polyesters, etc. The application of PC is limited by the notch sensitivity in thicker samples and by the processing properties. It is shown that addition of small amount of modifier such as polyolefins, ABS to PC can improve the notch sensivity and other mechanical and processing properties of net PC.

Acrylonitrile-butadiene-styrene (ABS) is the largest-volume engineering thermoplastic resin. It consists of two phases. The main construction of ABS is the styrene - acrylonitrile (SAN) that formulate a continuous matrix, and the second phase is referred to the composed of dispersed poly butadiene particles that contain the layers of SAN grafted on to their surface. The compatible of these two phases are prepared by SAN layers. ABS resins are commonly used in polymer blends, notably with PC to increase its mechanical properties. The PC/ABS blends are known to possess high impact strength and many other desirable properties. Since it can be easily processed.

PC/ABS blends have been widely utilized as an engineering thermoplastic. Many studies have been carried out on ABS/PC blends (Balakrishnan *et al.*, 1998; Chiang and Hwung, 1987; Choi *et al.*, 2000; Lee *et al.*, 2008; Ogoe *et al.*, 1996). Between the interesting finding of these studies are that ABS supplies the advantages of economics, processability and more certain impact resistance, while PC contributes the improvement of tensile, flexural, thermal properties and flammability to the blends. Investigation of the deformation behavior of PC/ABS alloy is important for their engineering application and extensive works have been carried out.

Notomi *et al*. (2000) has experimented the tensile deformation and fracture of PC/ABS blend. Fang *et al*. (2006) expanded a three-dimensional displacement measurement system to experimental study the large tensile deformation behavior of PC/ABS alloy. Seelig and van der Giessen (2002) numerically analyzed the localized plastic deformation in PC/ABS blend with respect to its dependence on strain rate. Yin *et al*.(2008) studied the viscoelastic deformation behavior of PC, ABS and PC/ABS blends with DMA and static relaxation tests.

Since thermoplastics, include PC/ABS blends, are easily combustible, flame-retarding formulation are desirable to reduce the probability of burning in the initial phase of a fire. The flame retardant makes disruption of the burning process so that it is terminated within an acceptable period of time, preferably before ignition actually occurs. Environmental regulations have restricted the use of halogen FR additives because of the generation of toxic gases and high levels of smoke this has initiated a search for alternative FR additives (Kashiwagi *et al.*, 2005).

Recently, worldwide interests in halogen-free flame retardants (FRs) have been mounting in the light of possible or potential health and environment hazards associated with the application of halogenated FRs (Morgan, 2006). Many kinds of halogen-free FRs have been developed, such as boron-containing compounds, phosphorus-containing compounds, nitrogen-containing compounds, silicon-containing compounds as well as some inorganic. Among them, the phosphorus-containing compounds or aryl phosphates are the most promising halogen-free FRs. For instance red phosphorus, triphenyl phosphate (TPP), resorcinol bis(biphenyl phosphate) (RDP), and bisphenol A bis(biphenyl phosphate) (BDP) are widely used in polyolefin, polycarbonate (PC), and PC/ABS alloys. The flame retardancy mechanisms of aryl phosphates in PC/ABS were examined by (Levchik and Weil, 2004). Within all flame retardants used in PC/ABS, aryl phosphates, including BDP would be a successful alternative for flame retardants containing halogen. The BDP volatilizes in the temperature interval of 320-500ºC, which is higher than that of RDP (280-460°C). Thus, BDP is the most thermally persistent of the three phosphates, probably because of its higher molecular weight (Levchik and Weil, 2004).

Nanoparticle fillers are highly attractive for this purpose because they can simultaneously improve the flammability and physical properties of polymer nanocomposites (Feyz *et al.*, 2011). Nanocomposite technology has been described as the new frontier of material science due to the employment of a few amount of nano filler which enhances mechanical, thermal, dimensional and barrier performance properties significantly (Alexandre and Dubois, 2000; LeBaron *et al.*, 1999). Among of nano fillers single layer two-dimensional graphene nanoplates

(GNPs) is considered as the strongest material along with high surface area and aspect ratio (Lee *et al.*, 2008). In addition, manufacturing cost for GNPs is lower compared to other high performance carbon-based nano structured materials, such as carbon nanotubes (CNTs) (Kuilla *et al.*, 2010). Therefore GNPs would be an interesting candidate as new reinforcing nano filler to enhance the properties of polymers (H. Kim *et al.*, 2010). A number of literatures have been dedicated to investigate potential of GNPs for improving the electrical, mechanical, thermal, and flame retardant properties of polymers. The present study focused on the effect of GNPs on the properties of PC/ABS blends. No systematic studies have been done so far to investigate the properties of PC/ABS/GNPs nanocomosites. Higginbotham *et al.* (2009) prepared graphene oxide (GO) with PC, ABS, and high-impact polystyrene for the purpose of evaluating the flammability reduction and material properties of the resulting systems which resulted in improvement in thermal, mechanical and electrical properties. Wang *et al.*(2011) also studied synergistic effect of GNPs on anti-dripping, fire resistance of intumescent flame retardant and mechanical properties of poly butylene succinate (PBS) composites due to the nano-reinforcement and unique physical properties of GNPs.

1.2 Problem Statement

Blending of polymers offers a simple and relatively cheap way to develop novel materials with a number of valuable properties. Studies on blending ABS with PC polymers had received considerably attentions due to their compatibility, rigidity and chemical resistance (Herpels and Mascia, 1990). In general PC/ABS blends are low hardness and expensive, so many researchers and industrialists are trying to introduce the alternative materials such as filler into this blend to enhance mechanical properties as well as improving the thermal properties at a cheaper cost. In recent years, studies on graphite derivatives (whether that of micro and nano-scale particles) incorporated into a single polymeric matrix such as EVA by Kim *et al.*(2009) and PC by Higginbotham *et al*. (2009) polymers has received much attention and favorable results had been obtained due its availability, low cost and high aspect ratio and non-toxicity. Detaile study on the characterization of PC/ABS/GNPs nanocomposites has not been reported in the literature.

The blends of PC/ABS are widely used for flame-retardant electrical and electronic enclosures. However, they are easily combustible mainly because of major drawback of ABS which is high flammable. Therefore, to overcome this problem variety of flame retardants were used however, further investigation on the affect of halogen free flame retardants such as BDP is needed. It is expected that the incorporation of BDP and GNPs would enhance the mechanical properties as well as thermal properties improvement. Meanwhile BDP can offer enhancement of flame retardancy of related blends. Moreover, the possibility of synergistic effect between GNPs and BDP for improvement of flame-retardancy and mechanical properties will be expected.

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1.3 Objectives of the Study

The overall aim of the present work was to improve the mechanical properties and flame resistant performance of PC/ABS blends by incorporation of GNPs and BDP into the polymer matrix. The objectives of this study are as follows:

1. To determine the effects of GNPs as nano fillers on mechanical, flame retardancy and thermal properties of PC/ABS blends.
2. To study on the effect of BDP as flame retardant on mechanical, flame retardancy and thermal properties of GNPs filled PC/ABS nanocomposites.

1.4 Scope of the Study

The scope of the study covered the preparation of the blend formulation to conducting various tests on the samples. According to Tjong and Meng (2000) and Jin *et al* (1998) the blends were consisted of a fixed PC/ABS blend composition of 70/30 blend. The halogen-free flame retardant which is BDP was introduced into the polymer matrix. In addition, the content of GNPs also varied to evaluate the effect of filler loading on the composites.

1. Fabrication of PC/ABS /BDP blends using twin screw extruder.
2. Fabrication of PC/ABS/ GNPs nanocomposite using twin screw extruder.
3. Fabrication of PC/ABS/ BDP/GNPs using twin screw extruder.
4. Fabrication of The composite and nanocomposite specimens via injection molding for analysis.
5. Evaluating the physical and mechanical properties of the prepared blend and nanocomposite by means of tensile strength, tensile modulus, and elongation at break, flexural test and Izod impact test.
6. Characterizing the thermal and structural properties of the of the prepared blend and nanocomposite using, thermogravimetric analysis (TGA), field emission scanning electron microscopy (FESEM) and Fourier transform infra-red (FTIR) spectroscopy.
7. Evaluating the flame retardancy properties of the prepared blend and nanocomposite using UL-94 and limiting oxygen index (LOI).

Alexandre, M. andDubois, P. (2000). Polymer-layered silicate nanocomposites: preparation, properties and uses of a new class of materials. *Materials Science and Engineering: R: Reports, 28*(1), 1-63.

Balakrishnan, S., Neelakantan, N. R., Saheb, D. N. andJog, J. P. (1998). Rheological and morphological behaviour of blends of polycarbonate with unmodified and maleic anhydride grafted ABS. *Polymer, 39*(23), 5765-5771.

Chiang, W.-Y. andHwung, D.-S. (1987). Properties of polycarbonate/acrylonitrile-butadiene-styrene blends. *Polymer Engineering & Science, 27*(9), 632-639.

Choi, H. J., Park, S. H., Kim, J. K. andJun, J. I. (2000). Effects of acrylonitrile content on PC/ABS alloy systems with a flame retardant. *Journal of Applied Polymer Science, 75*(3), 417-423.

Fang, Q.-Z., Wang, T. J. andLi, H.-M. (2006). Large tensile deformation behavior of PC/ABS alloy. *Polymer, 47*(14), 5174-5181.

Feyz, E., Jahani, Y. andEsfandeh, M. (2011). Effect of a nanoclay/triphenyl phosphate hybrid system on the fire retardancy of polycarbonate/acrylonitrile–butadiene–styrene blend. *Journal of Applied Polymer Science, 120*(6), 3435-3442.

Herpels, J. andMascia, L. (1990). Effects of styrene-acrylonitrile/butadiene ratio on the toughness of polycarbonate/ABS blends. *European polymer journal, 26*(9), 997-1003.

Higginbotham, A. L., Lomeda, J. R., Morgan, A. B. andTour, J. M. (2009). Graphite oxide flame-retardant polymer nanocomposites. *ACS Applied Materials & Interfaces, 1*(10), 2256-2261.

Jin, D., Shon, K., Jeong, H. andKim, B. (1998). Compatibility enhancement of ABS/polycarbonate blends. *Journal of Applied Polymer Science, 69*(3), 533-542.

Kashiwagi, T., Du, F., Douglas, J. F., Winey, K. I., Harris, R. H. andShields, J. R. (2005). Nanoparticle networks reduce the flammability of polymer nanocomposites. [10.1038/nmat1502]. *Nat Mater, 4*(12), 928-933.

Kim, H., Miura, Y. andMacosko, C. W. (2010). Graphene/polyurethane nanocomposites for improved gas barrier and electrical conductivity. *Chemistry of Materials, 22*(11), 3441-3450.

Kim, S., Do, I. andDrzal, L. T. (2009). Multifunctional xGnP/LLDPE nanocomposites prepared by solution compounding using various screw rotating systems. *Macromolecular Materials and Engineering, 294*(3), 196-205.

Kuilla, T., Bhadra, S., Yao, D., Kim, N. H., Bose, S. andLee, J. H. (2010). Recent advances in graphene based polymer composites. *Progress in Polymer Science, 35*(11), 1350-1375.

LeBaron, P. C., Wang, Z. andPinnavaia, T. J. (1999). Polymer-layered silicate nanocomposites: an overview. *Applied Clay Science, 15*(1), 11-29.

Lee, C., Wei, X., Kysar, J. W. andHone, J. (2008). Measurement of the elastic properties and intrinsic strength of monolayer graphene. *Science, 321*(5887), 385-388.

Levchik, S. V. andWeil, E. D. (2004). Thermal decomposition, combustion and flame retardancy of epoxy resins—a review of the recent literature. *Polymer International, 53*(12), 1901-1929.

Morgan, A. B. (2006). Flame retarded polymer layered silicate nanocomposites: a review of commercial and open literature systems. *Polymers for Advanced Technologies, 17*(4), 206-217.

Notomi, M., Kishimoto, K., Wang, T. J. andShibuya, T. (2000). Tensile and fracture behaviors of PC/ABS polymer alloy. *Key Engineering Materials, 183*, 779-784.

Ogoe, S. A., Grelle, P. F., Watkins, T. J., Masloski, P. J. andKallman, M. A. (1996). 'Go with the flow!': Advantages of high melt flow rate ignition resistant polycarbonate versus IR PC/ABS blends. *Polymer Degradation and Stability, 54*(2–3), 181-188.

Seelig, T. andvan der Giessen, E. (2002). Localized plastic deformation in ternary polymer blends. *International Journal of Solids and Structures, 39*(13–14), 3505-3522.

Tjong, S. andMeng, Y. (2000). Effect of reactive compatibilizers on the mechanical properties of polycarbonate/poly (acrylonitrile-butadiene-styrene) blends. *European polymer journal, 36*(1), 123-129.

Wang, X., Song, L., Yang, H., Lu, H. andHu, Y. (2011). Synergistic Effect of Graphene on Antidripping and Fire Resistance of Intumescent Flame Retardant Poly (butylene succinate) Composites. *Industrial & Engineering Chemistry Research, 50*(9), 5376-5383.

Yin, Z. N., Fan, L. F. andWang, T. J. (2008). Experimental investigation of the viscoelastic deformation of PC, ABS and PC/ABS alloys. *Materials Letters, 62*(17–18), 2750-2753.

8.

REFERENCES

Alexandre, M. and Dubois, P. (2000). Polymer-layered silicate nanocomposites: preparation, properties and uses of a new class of materials. *Materials Science and Engineering: R: Reports*, *28*(1), 1-63.

Balakrishnan, S., Neelakantan, N. R., Saheb, D. N. andJog, J. P. (1998). Rheological and morphological behaviour of blends of polycarbonate with unmodified and maleic anhydride grafted ABS. *Polymer*, *39*(23), 5765-5771.

Balandin, A. A., Ghosh, S., Bao, W., Calizo, I., Teweldebrhan, D., Miao, F., et al. (2008). Superior thermal conductivity of single-layer graphene. *Nano letters*, *8*(3), 902-907.

Bernhard, S., Kristin, H. R. and Martin, B. (2012). Synergistic Use of Talc in Halogen-Free Flame Retarded Polycarbonate/Acrylonitrile-Butadiene-Styrene Blends *Fire and Polymers VI: New Advances in Flame Retardant Chemistry and Science* (Vol. 1118, pp. 15-36): American Chemical Society.

Brydson, J. A. (1995). *Thermoplastic elastomers: properties and applications* (Vol. 7): iSmithers Rapra Publishing.

Brydson, J. A. (1999). *Plastics materials*: Butterworth-Heinemann.

Chiang, W.-Y. and Hwung, D.-S. (1987). Properties of polycarbonate/acrylonitrile-butadiene-styrene blends. *Polymer Engineering & Science*, *27*(9), 632-639.

Choi, H. J., Park, S. H., Kim, J. K. and Jun, J. I. (2000). Effects of acrylonitrile content on PC/ABS alloy systems with a flame retardant. *Journal of Applied Polymer Science, 75*(3), 417-423.

Colborn, R., Buckley, D., Adams, M., Buckley, D. andColburn, R. (1993). *Acrylonitrile Butadiene Styrene Polymers* (Vol. 70): iSmithers Rapra Publishing.

De Andres, P., Ramírez, R. and Vergés, J. A. (2008). Strong covalent bonding between two graphene layers. *Physical Review B, 77*(4), 045403.

Despinasse, M.-C. and Schartel, B. (2012). Influence of the structure of aryl phosphates on the flame retardancy of polycarbonate/acrylonitrile–butadiene–styrene. *Polymer Degradation and Stability*, *97*(12), 2571-2580.

Dick, J. S. (1987). Compounding Materials for the Polymer Industries: A Concise Guide to Polymers, Rubbers, Adhesives, and Coatings. *Noyes Publications, 1987*, 288.

Du, X., Skachko, I., Barker, A. and Andrei, E. Y. (2008). Approaching ballistic transport in suspended graphene. *Nature nanotechnology*, *3*(8), 491-495.

Fang, Q.-Z., Wang, T. J. and Li, H.-M. (2006). Large tensile deformation behavior of PC/ABS alloy. *Polymer*, *47*(14), 5174-5181.

Feyz, E., Jahani, Y. and Esfandeh, M. (2011). Effect of a nanoclay/triphenyl phosphate hybrid system on the fire retardancy of polycarbonate/acrylonitrile–butadiene–styrene blend. *Journal of Applied Polymer Science*, *120*(6), 3435-3442.

Fire, F. L. (1991). Combustibility of plastics. *Van Nostrand Reinhold, 115 Fifth Ave, New York, New York 10003, USA, 1991. 326*.

Fox, D. W. and Allen, R. B. (1985). Compatibility. *Wiley-Interscience, Encyclopedia of Polymer Science and Engineering., 3*, 758-775.

Geng, Y., Li, J., Wang, S. J. and Kim, J. K. (2008). Amino functionalization of graphite nanoplatelet. *Journal of Nanoscience and Nanotechnology, 8*(12), 6238-6246.

Greco, R. andSorrentino, A. (1994). Polycarbonate/ABS blends: a literature review. *Advances in Polymer Technology, 13*(4), 249-258.

Green, J. (1996). A review of phosphorus-containing flame retardants. *Journal of Fire Sciences, 14*(5), 353-366.

Han, D., Yan, L., Chen, W., Li, W. and Bangal, P. (2011a). Cellulose/graphite oxide composite films with improved mechanical properties over a wide range of temperature. *Carbohydrate Polymers, 83*(2), 966-972.

Han, D., Yan, L., Chen, W., Li, W. and Bangal, P. R. (2011b). Cellulose/graphite oxide composite films with improved mechanical properties over a wide range of temperature. *Carbohydrate Polymers, 83*(2), 966-972.

Hassan, A. and Wong, Y. J. (2005). Mechanical properties of high impact Abs/Pc blends-effect of blend ratio.

Herpels, J. and Mascia, L. (1990). Effects of styrene-acrylonitrile/butadiene ratio on the toughness of polycarbonate/ABS blends. *European polymer journal, 26*(9), 997-1003.

Higginbotham, A. L., Lomeda, J. R., Morgan, A. B. and Tour, J. M. (2009). Graphite oxide flame-retardant polymer nanocomposites. *ACS Applied Materials & Interfaces, 1*(10), 2256-2261.

Huang, H.-D., Ren, P.-G., Chen, J., Zhang, W.-Q., Ji, X. and Li, Z.-M. (2012). High barrier graphene oxide nanosheet/poly (vinyl alcohol) nanocomposite films. *Journal of Membrane Science, 409*, 156-163.

Huang, H., Tian, M., Liu, L., Liang, W. and Zhang, L. (2006). Effect of particle size on flame retardancy of Mg (OH) 2 filled ethylene vinyl acetate copolymer composites. *Journal of Applied Polymer Science, 100*(6), 4461-4469.

Jin, D., Shon, K., Jeong, H. and Kim, B. (1998). Compatibility enhancement of ABS/polycarbonate blends. *Journal of Applied Polymer Science, 69*(3), 533-542.

Kashiwagi, T., Du, F., Douglas, J. F., Winey, K. I., Harris, R. H. and Shields, J. R. (2005). Nanoparticle networks reduce the flammability of polymer nanocomposites. [10.1038/nmat1502]. *Nat Mater, 4*(12), 928-933.

Kim, H., Keskkula, H. and Paul, D. (1990). Toughening of SAN copolymers by an SAN emulsion grafted rubber. *Polymer, 31*(5), 869-876.

Kim, H., Miura, Y. and Macosko, C. W. (2010). Graphene/polyurethane nanocomposites for improved gas barrier and electrical conductivity. *Chemistry of Materials, 22*(11), 3441-3450.

Kim, S., Do, I. and Drzal, L. T. (2009). Multifunctional xGnP/LLDPE nanocomposites prepared by solution compounding using various screw rotating systems. *Macromolecular Materials and Engineering, 294*(3), 196-205.

King, J. A., Via, M. D., Morrison, F. A., Wiese, K. R., Beach, E. A., Cieslinski, M. J., et al. (2012). Characterization of exfoliated graphite nanoplatelets/polycarbonate composites: electrical and thermal conductivity, and tensile, flexural, and rheological properties. *Journal of Composite Materials, 46*(9), 1029-1039.

Krache, R. and Debbah, I. (2011). Some mechanical and thermal properties of PC/ABS blends. *Mater Sci Appl, 2*, 404-410.

Kroto, H. W., Heath, J. R., O'Brien, S. C., Curl, R. F. and Smalley, R. E. (1985). C 60: buckminsterfullerene. *Nature, 318*(6042), 162-163.

Kuilla, T., Bhadra, S., Yao, D., Kim, N. H., Bose, S. andLee, J. H. (2010). Recent advances in graphene based polymer composites. *Progress in Polymer Science, 35*(11), 1350-1375.

Kumar, A. a. G., R. K. (2003). Fundamental of polymer engineerimg. *Marcel Decker., New York.*

LeBaron, P. C., Wang, Z. and Pinnavaia, T. J. (1999). Polymer-layered silicate nanocomposites: an overview. *Applied Clay Science, 15*(1), 11-29.

Lee, C., Wei, X., Kysar, J. W. and Hone, J. (2008). Measurement of the elastic properties and intrinsic strength of monolayer graphene. *Science, 321*(5887), 385-388.

Levchik, S. V. and Weil, E. D. (2005). Overview of recent developments in the flame retardancy of polycarbonates. *Polymer International, 54*(7), 981-998.

Levchik, S. V. and Weil, E. D. (2006). A review of recent progress in phosphorus-based flame retardants. *Journal of Fire Sciences*, *24*(5), 345-364.

Levchik, S. V., Bright, D. A., Alessio, G. R. and Dashevsky, S. (2001). New halogen free fire retardant for engineering plastic applications. *Journal of Vinyl and Additive Technology, 7*(2), 98-103.

Levchik, S. V., Bright, D. A., Moy, P. and Dashevsky, S. (2004). New developments in fire retardant non halogen aromatic phosphates. *Journal of Vinyl and Additive Technology*, *6*(3), 123-128.

Levchik, S. V. and Weil, E. D. (2004). Thermal decomposition, combustion and flame retardancy of epoxy resins—a review of the recent literature. *Polymer International*, *53*(12), 1901-1929.

Liang, J., Huang, Y., Zhang, L., Wang, Y., Ma, Y., Guo, T., et al. (2009). Molecular-Level Dispersion of Graphene into Poly (vinyl alcohol) and Effective

Reinforcement of their Nanocomposites. *Advanced Functional Materials, 19*(14), 2297-2302.

Lu, S. Y. and Hamerton, I. (2002). Recent developments in the chemistry of halogen-free flame retardant polymers. *Progress in Polymer Science, 27*(8), 1661-1712.

Lutz, J. T. and Grossman, R. F. (2001). Polymer modifiers and additives. *Marcel! Dekker, Inc, 270 Madison Avenue, New York, NY 10016, USA, 2001. 510.*

Mahmoudian, S., Wahit, M. U., Imran, M., Ismail, A. and Balakrishnan, H. (2012). A facile approach to prepare regenerated cellulose/graphene nanoplatelets nanocomposite using room-temperature ionic liquid. *Journal of Nanoscience and Nanotechnology, 12*(7), 5233-5239.

Matchimapiro, T., Sornthummalee, P., Pothisiri, T. and Rimdisit, S. (2008). Impact Behaviors and Thermomechanical Properties of TPP-Filled Polycarbonate/Acrylonitrile-Butadiene-Styrene Blends. *Journal of Metals, Materials and Minerals, 18*(2), 187-190.

Meyer, J. C., Geim, A., Katsnelson, M., Novoselov, K., Booth, T. and Roth, S. (2007). The structure of suspended graphene sheets. *Nature, 446*(7131), 60-63.

Morgan, A. B. and Gilman, J. W. (2012). An overview of flame retardancy of polymeric materials: application, technology, and future directions. *Fire and Materials*.

Morgan, A. B. (2006). Flame retarded polymer layered silicate nanocomposites: a review of commercial and open literature systems. *Polymers for Advanced Technologies*, *17*(4), 206-217.

Notomi, M., Kishimoto, K., Wang, T. J. and Shibuya, T. (2000). Tensile and fracture behaviors of PC/ABS polymer alloy. *Key Engineering Materials, 183*, 779-784.

Novoselov, K., Geim, A., Morozov, S., Jiang, D., Zhang, Y., Dubonos, S., et al. (2004). Electric field effect in atomically thin carbon films. *Science, 306*(5696), 666-669.

Ogoe, S. A., Grelle, P. F., Watkins, T. J., Masloski, P. J. and Kallman, M. A. (1996). 'Go with the flow!': Advantages of high melt flow rate ignition resistant polycarbonate versus IR PC/ABS blends. *Polymer Degradation and Stability, 54*(2–3), 181-188.

Park, S. and Ruoff, R. S. (2009). Chemical methods for the production of graphenes. *Nature nanotechnology, 4*(4), 217-224.

Paul, D. R. and Newman, S. N. (1978). Polymer Blends. *Academic, New York*.

Pawlowski, K. H., Schartel, B., Fichera, M. A. and Jäger, C. (2010). Flame retardancy mechanisms of bisphenol A bis (diphenyl phosphate) in combination with zinc borate in bisphenol A polycarbonate/acrylonitrile–butadiene–styrene blends. *Thermochimica Acta, 498*(1), 92-99.

Pawlowski, K. H. and Schartel, B. (2007). Flame retardancy mechanisms of triphenyl phosphate, resorcinol bis (diphenyl phosphate) and bisphenol A bis (diphenyl phosphate) in polycarbonate/acrylonitrile–butadiene–styrene blends. *Polymer International, 56*(11), 1404-1414.

Perret, B. and Schartel, B. (2009). The effect of different impact modifiers in halogen-free flame retarded polycarbonate blends–I. Pyrolysis. *Polymer Degradation and Stability, 94*(12), 2194-2203.

PlasticsEurope. (2009). The Compelling Facts About Plastics 2009 (PEMRG, Brussels, Belgium, 2009).

Roco, M. C. (2003). Broader societal issues of nanotechnology. *Journal of Nanoparticle Research, 5*(3), 181-189.

Schaefer, D. W. and Ryan, S. (2007). How nano are nanocomposites? *Macromolecules, 40*(24), 8501-8517.

Sehanobish, K. and Traugott, T. (2006). Plastics and elastomers: automotive applications.

Seelig, T. andvan der Giessen, E. (2002). Localized plastic deformation in ternary polymer blends. *International Journal of Solids and Structures, 39*(13–14), 3505-3522.

Sinha Ray, S. and Okamoto, M. (2003). Polymer/layered silicate nanocomposites: a review from preparation to processing. *Progress in Polymer Science, 28*(11), 1539-1641.

Stankovich, S., Dikin, D. A., Dommett, G. H. B., Kohlhaas, K. M., Zimney, E. J., Stach, E. A., et al. (2006). Graphene-based composite materials. *Nature, 442*(7100), 282-286.

Statler, D., Stajduhar, E. and Gupta, R. K. (2008). Flame Retardancy of Polycarbonate upon Repeated Recycling. *Journal of Fire Sciences, 26*(4), 331-350.

Suarez, H., Barlow, J. and Paul, D. (2003). Mechanical properties of ABS/polycarbonate blends. *Journal of Applied Polymer Science, 29*(11), 3253-3259.

Švec, P. (1990). *Styrene-based plastics and their modification*: Ellis Horwood.

Tjong, S. and Meng, Y. (2000). Effect of reactive compatibilizers on the mechanical properties of polycarbonate/poly (acrylonitrile-butadiene-styrene) blends. *European polymer journal, 36*(1), 123-129.

Utracki, L. (1998). *Commercial polymer blends*: Kluwer Academic Publishers.

Utracki, L. A. (2002). Introduction to polymer blends. . *Polymer Blens Handbook, Kluwer Academic Publishers. London, 1*.

Utracki, L. and Favis, B. (1989). Polymer alloys and blends. *Handbook of Polymer Science and Technology, Marcel Dekker, Inc., New York*, 121-201.

Vadukumpully, S., Paul, J., Mahanta, N. and Valiyaveettil, S. (2011). Flexible conductive graphene/poly (vinyl chloride) composite thin films with high mechanical strength and thermal stability. *Carbon, 49*(1), 198-205.

Wang, X., Song, L., Yang, H., Lu, H. and Hu, Y. (2011). Synergistic Effect of Graphene on Antidripping and Fire Resistance of Intumescent Flame Retardant Poly (butylene succinate) Composites. *Industrial & Engineering Chemistry Research, 50*(9), 5376-5383.

Ward, I. and Hadley, D. (1993). An Introduction to the mechanical properties of solid polymers, 1993: Wiley.

Wawrzyn, E., Schartel, B., Seefeldt, H., Karrasch, A. and Ja ger, C. (2012). What Reacts with What in Bisphenol A Polycarbonate/Silicon Rubber/Bisphenol A Bis (diphenyl phosphate) during Pyrolysis and Fire Behavior? *Industrial & Engineering Chemistry Research, 51*(3), 1244-1255.

Yin, Z. N., Fan, L. F. and Wang, T. J. (2008). Experimental investigation of the viscoelastic deformation of PC, ABS and PC/ABS alloys. *Materials Letters, 62*(17–18), 2750-2753.

Zhao, X., Zhang, Q., Chen, D. andLu, P. (2010). Enhanced mechanical properties of graphene-based poly (vinyl alcohol) composites. *Macromolecules, 43*(5), 2357-2363.