The effects of nano-sized carbon black content and particle sizes on the properties of carbon/phenolic composite bipolar plates

Rajeev K. Gautam
Advanced Nanoengineering Materials Laboratory,
Material Science Programme, Indian Institute of
Technology Kanpur-208016, India
Email: rajeevg@iitk.ac.in

Kamal K. Kar
Advanced Nanoengineering Materials Laboratory,
Department of Materials Science Programme and
Department of Mechanical Engineering, Indian
Institute of Technology Kanpur-208016, India

***Abstract*—A major component which significantly influences the cost and weight of PEM fuel cell is bipolar plate. Hence, development of low cost and light materials with superior mechanical, thermal and electrical properties are essential for bipolar plates. In this study, carbon / phenolic composite plates have been investigated using nano-sized carbon black (NCB) as conducting fillers in phenolic resin by simple mold compression method. The effects of variations in NCB content and its particles size gradation on mechanical, thermal and electrical properties of composite bipolar plates have been investigated. The composite plates having 25 wt% of NCB content shows optimum values for compressive, flexural, and dynamic mechanical properties. However, the electrical conductivity and surface hardness of composite plates are increasing with increasing NCB content. Whereas, the flexural, compressive, surface hardness, dynamic mechanical properties are decreasing and electrical conductivity is increasing with increasing NCB particles size. In addition to this, the composite plates are thermally stable up to 300°C for both the cases, which successfully meet the DOE requirements for bipolar plates of PEM fuel cell.**

Keywords— Bipolar plate, carbon/polymer composites, fuel cell, mechanical properties

1.0 INTRODUCTION

Polymer electrolyte membrane (PEM) fuel cell has received huge attention recently because of increasing energy consumption, limited energy resources and increasing environmental concern [1-5]. A PEM fuel cell is an electrochemical device which efficiently converts chemical energy of fuel into electrical energy with zero emission at low temperature (80-100°C) [6]. Hence, PEM fuel cells can be utilized as most promising power sources in mobile, transportation, and stationary applications [7, 8]. However, the enormous cost, weight, long term durability are the main factors which hinder the widespread commercialization of these devices [5, 9, 10]. Bipolar plate is the major component of a PEM fuel cell which makes up almost 80% [11] by weight and 40% [12] by cost of the fuel cell stack. Also, it facilitate various important functions such as connection of individual cells electrically in series, facilitate gas/fuel through flow channels stamped on plate surface, helps in heat and water management during fuel cell operation, and provide mechanical support to membrane electrode assembly [13, 14]. Hence, bipolar plate materials must have high electrical conductivity, good mechanical properties, and excellent thermal stability. Various studies based on graphite and metals have been made to fulfill aforesaid requirements of bipolar plate materials [15-19]. However, weak mechanical properties of graphite and highly corrosive nature of metals limit their use as bipolar plate materials in PEM fuel cell [20, 21]. Hence, new efforts have been made to investigate carbon/polymer based composite materials to replace traditional metallic and graphite bipolar plates used in PEM fuel cell [22-25]. Carbon/polymer composites have various advantages over graphite and metal based bipolar plates like they have low cost and are light in weight, can be machined easily, exhibit mechanical and chemical stability with low contact resistance [26-28]. However, it is essential for these bipolar plates to achieve all the aforesaid requirements and accomplishes its various functions. The major objective of this work is to develop low cost and light weight carbon/phenolic composites, which can achieve the maximum requirements of a bipolar plate as per target values set by Department of Energy, United State of America (DOE) for bipolar plates in PEM fuel cell. Therefore, in order to develop such composite bipolar plates, nano-sized carbon black (NCB) as a conducting filler and resole-type phenol formaldehyde resin as a polymer matrix, have been used in this study. The NCB used as conducting filler, is elemental carbon in the form of spherical particles, and widely used as filler material in the polymer matrix to tailor electrical, thermal, mechanical, and optical properties of the end product. The most important characteristic of carbon black is its high surface area, since the particles are small in size; therefore the specific surface area is large. This high surface area facilitates excellent interaction between filler and polymer matrix, which delivers composites with improved properties. In this work, carbon/phenolic composite plates have been developed by simple mold compression method. Here the effect of NCB loading and the variation in particle sizes on the properties of composite plates are studied in detail.

2.0 EXPERIMENTAL

2.1 Materials

The composites are prepared using resole type phenolic resin (ABRON 100 WS) as a polymer matrix. The resole-type phenol formaldehyde resin has been obtained in the liquid form from M/S ABR organics, India. The specific gravity, viscosity, volatile content and solid content of the resin were 1.12-1.16, 100-300 CPS at 30°C, 32-38% and 60-65%, respectively. The curing agent used is p-toluene sulfonic acid (PTSA) with a melting temperature of 105°C and molecular weight of 192 g mol^{-1} and has been supplied by M/S Loba Chemie Pvt. Ltd. India. Here, the electrically conductive NCB of five different grades N220, N326, N330, N660, and N774 have been used as major filler materials are received from M/S Kankani Brothers Ltd. India. The properties of different grades of NCB are provided in Table I.

TABLE I: PHYSICAL PROPERTIES OF NANO-SIZED CARBON BLACK

ASTM number	Distribution of particle size (nm)	Average particle size (nm)	BET N_2SA (m^2/kg)	Pour density (kg/m^3)
N220	10-20	15	114-124	346±25
N326	20-30	25(a)	73-83	460±25
N330	20-30	25(b)	73-83	376±25
N660	50-60	55	31-39	420±25
N774	60-70	65	27-33	480±25

2.2 Specimen Preparation

The p-toluen sulfonic act as a catalyst or curing agent has been received in the form of powder. So first of all, p-toluen sulfonic acid solution containing little amount of distilled water (ca. 10mL/g) has been prepared. The catalyst solution is then added to phenolic resin and mixed thoroughly with the help of a glass rod for 1 min. Again it has been mixed with pre-weighed amount of NCB thoroughly for 15 min to obtain a uniform mixture of carbon fillers and phenolic resin. The mixture is then poured in the cavities of differently sized molds, which are placed in between the plates of hydraulic press and after 15-20 min of normal curing a load has been applied slowly up to 15 MPa at room temperature and kept for 10 h. Finally, after curing for 10 h, solid composite plates have been retrieved from the molds for further testing.

2.3 Characterizations

The prepared composite plates have been characterized for bulk density, porosity, compressive strength, flexural strength, hardness, electrical conductivity and dynamic mechanical analysis. An average of four to five characterization samples have been reported in each case. The bulk density (B_d) and the water density (W_d) of the plates have been measured as per ASTM C559 and D792. Porosity of composite plates has been measured by water density method which can be calculated by using *Eq. 1.*[7]

$$\text{Porosity} = \left(1 - \frac{B_\text{d}}{W_\text{d}}\right) \times 100\% \quad (1)$$

Where B_d is the ratio of the weight in air to volume of the sample and W_d=A/(A-B)d_w; where *A* is the weight of the sample in air, *B* is the weight of sample in water, and d_w is the density of water. The flexural strength and flexural modulus of the composite bipolar plates of size 60mm × 10mm × 5mm have been determined by the three point bending test using Zwick Roell UTM (MODEL Z010) as per ASTM D790 at a crosshead speed of 0.5 mm min^{-1} and the compressive strength and compressive modulus have been measured as per ASTM C695 at a crosshead speed of 0.5 mm min^{-1}. The surface hardness of the composite plates has been measured using micro-Vickers Hardness System, Qualitest North America (MODEL QV-1000DM). The hardness has been measured by penetrating diamond pyramid indenter under a load of 200g for 10s onto the surface of composites. The dynamic mechanical properties i.e., storage modulus (E'), loss modulus (E'') and tanδ (plates size: 50mm × 12mm × 1±0.8mm) have been measured by Pyris Diamond DMA, Parkin Elmer Instruments, USA. The DMA tests have been carried out in three-point bending over a temperature range of 50 to 300°C and heating rate of 10°C/min in a nitrogen atmosphere at frequency of 1 Hz. The electrical conductivity has been measured by the four probe method at a constant current source. Kiethley 6221 setup has been used to provide constant current supply, and the voltage drop (V) between two probes 2 mm apart has been measured by a microvoltmeter (DMV-001) at 30°C. Thermal stability of composite plates has been investigated through thermogravimetric analysis (TGA) under nitrogen atmosphere (flow rate of N_2, 200 mL/min) from 30 to 700°C at a heating rate of 5°C/min. (Pyris Diamond TG/DTA). Microstructures of composites have been studied by scanning electron microscopy (Zeiss, model EVOMA15) and optical microscopy (model RMM-2), Redical Instruments, India.

2.3 Preparation of Carbon/Phenolic Resin Composites Bipolar Plates

Carbon/phenolic composite plates have been prepared in two phases by compression molding. In phase 1, the composite plates have been prepared with variation of NCB (Grade, N330; particle size, 25 nm) content from 5 to 40 wt% in phenolic resin. In phase 2, the NCB content has been kept fixed at its optimized value of 25 wt%, while varying the particles size in phenolic resin. The particles sizes of different grades NCB are mentioned in Table I. The curing agent (PTSA) supplied has been in the form of powder, and its uniform mixing in the resin is difficult to achieve. PTSA solution containing 10 wt% is prepared in distilled water. Then, measured quantity of resin has been mixed with pre-weighed amount of NCB filler, to which pre-weighed amount of PTSA solution is added, and the mixture is gently and thoroughly stirred by a glass rod to reduce the entrapment of air bubbles. This is then poured in different sized molds, and is allowed to cure at 30°C. After semi curing, the samples have been kept under a mold pressure of 15 MPa for 10 h. Finally, after curing for 10 h, solid composite plates have been retrieved for further testing.

3. RESULTS and DISCUSSION

3.1 Density and Porosity of Carbon/Phenolic Resin Composite Bipolar Plates

The density and porosity measured for all these carbon/phenolic composites is shown in Fig. 1. Upon varying NCB content from 5 to 40 wt%, the bulk density of carbon/phenolic composite plates moderately decreases from 1.72 to 1.33 g cm^{-3} and porosity increases from 1.87 to 5.25%. The NCB used in this study is low density materials with high surface area. Hence, with increase in the content of NCB, it became difficult for each NCB particle to be fully wetted by phenolic resin in composite. As a result, at high NCB content, NCB particles got agglomerated, which developed closed porosity in the composites. This has been further revealed upon SEM analysis as shown in Fig. 5. This causes an increase in the porosity and corresponding decrease in the bulk density. On the other hand, the effect of particle size on the bulk density and porosity has shown in Fig. 2 reveals that the density of composites almost remains unaffected with decrease in NCB particle size. Also, the variation of NCB particle size does not make any significant change in the porosity of composites. However, the porosity of composite plates moderately increases from 3.77% to 3.88% with decreasing particle size from 65 to 15 nm.

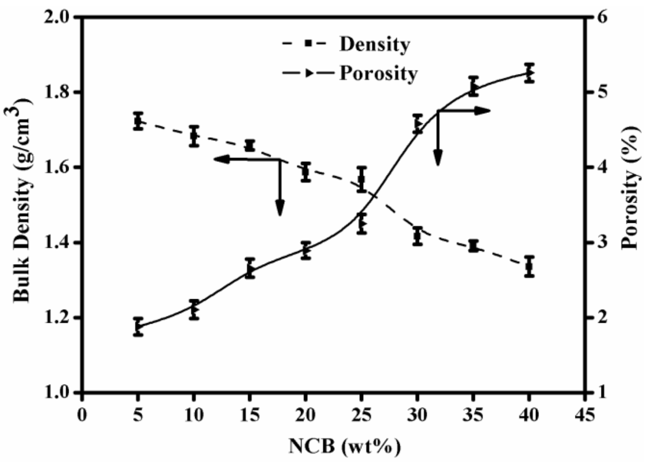

Fig. 1: Variation in bulk density and porosity with increasing NCB content.

The overall surface area of NCB particles increases with decreasing particle size; hence the particles are not fully wetted by the available resin, which leads to the formation of micro-sized pores in the composites. However, all composites possess excellent density in comparison to DOE target of 1.90 g cm^{-3}, and make them suitable to use as bipolar plate materials.

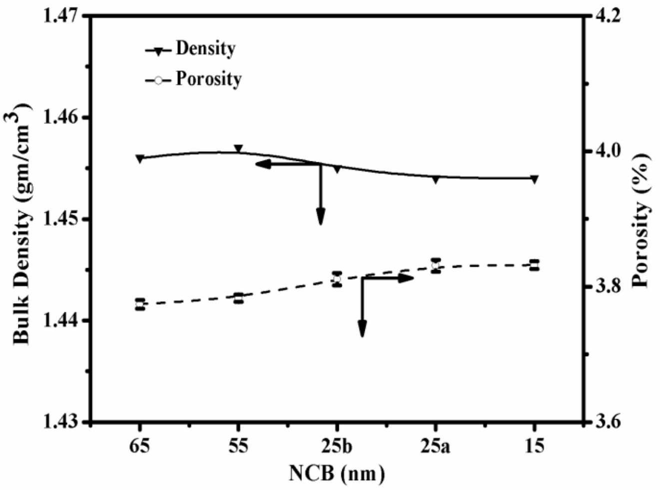

Fig. 2: Effect of NCB particle size on the density and porosity of the composite plate.

3.2 Flexural and Compressive Properties of Carbon/Phenolic Resin Composite Bipolar Plates

The variations in flexural strength and flexural modulus with increasing NCB content can be seen in Fig. 3. As observed, the strength as well as modulus increases up to 25 wt% of NCB content, after which they start decreasing. Initially, for 5 wt% of NCB content, flexural strength and modulus are 30 MPa and 2.5 GPa. The maximum strength and modulus are 54.33 MPa and 6 GPa at 25 wt% of NCB content. The increase in strength and modulus up to 25 wt% can be explain as follows: It has been assumed, at lower NCB content (less than 25 wt%), NCB particles can mix easily in phenolic resin and provide better interconnectivity which facilitate higher mechanical strength, but at higher content of NCB (beyond 25 wt%), NCB content crosses the percolation threshold. Thus, due to the lack of phenolic resin, NCB particles could not be fully wetted and got agglomerated, which can clearly be seen in the SEM images indicated by arrows in Fig. 5. From the SEM images, it has been observed that at higher concentration of NCB content, the agglomerated NCB particles and micro-voids created a weak interaction between NCB particles and phenolic resin, which led to a decrease in flexural strength and modulus. The variations of compressive strength and modulus with increasing NCB content can be seen in Fig. 4. The compressive strength and modulus progressively increase with increasing NCB content up to 25 wt% and thereafter start decreasing. Higher concentration of NCB content in composites beyond the critical limit causes increase in agglomeration of NCB particles. This leads to brittle behavior and micro-voids formation, which results in reduction of compressive strength and modulus. The maximum values flexural and compressive strength observed at 25 wt% of NCB content, are 54.33 MPa and 70.66 MPa, which are quite higher than the DOE targets (flexural strength: 25 MPa and compressive strength: 50 MPa). These excellent mechanical properties made these composites more suitable materials, to be used as bipolar plates.

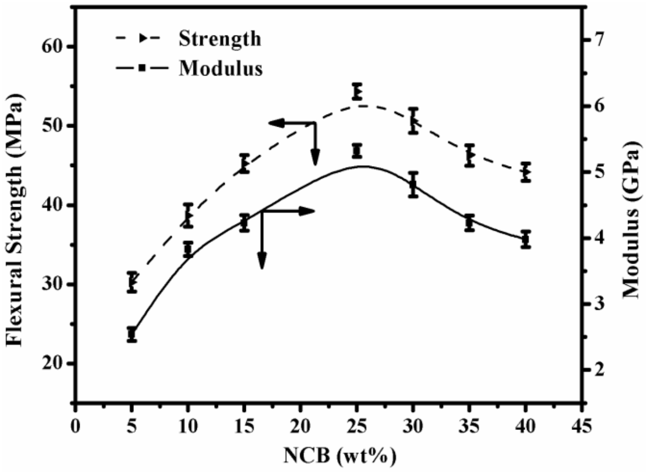

Fig. 3: Variation in flexural strength and modulus with increasing NCB content.

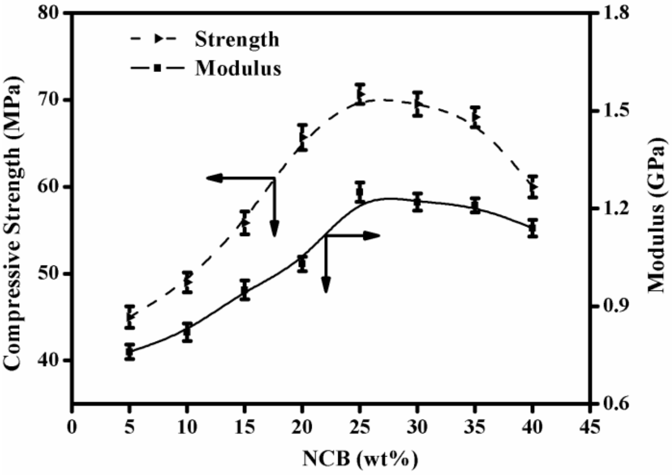

Fig. 4: Variation in compressive strength and modulus with increasing NCB content.

Fig. 6 and 7, show that the flexural strength, compressive strength, and corresponding modulus of composites are considerably reliant on the size of NCB particles. It can be seen that the flexural strength and modulus have increased with decreasing particle size of NCB. Moreover, the compressive strength and modulus of composite follows the same trend and increases with decreasing particle size of NCB as shown in Fig. 7. The dependence of flexural and compressive strength, on NCB particle size can be explained on the basis of interaction between NCB particles and phenolic resin. The small size NCB particle owns more surface area in comparison to large NCB particles. Therefore, the small size NCB particles exhibit better absorbing ability than large NCB particles, which provides a strong adhesion between NCB and phenolic resin. Furthermore, the increasing NCB particle size results in a significant increase in the numbers of voids. This can be justified from the optical micrographs of the composite plates prepared with different NCB particle sizes (see Fig. 8). Thus, flexural and compressive strength of the composite plates increase with decrease in NCB particle size. The maximum flexural strength and modulus observed are 53.82 MPa and 5.29 GPa for NCB with particle size of 15 nm, whereas the minimum of flexural strength and modulus are 48.34 MPa and 4.62 GPa for NCB with particle size of 65 nm.

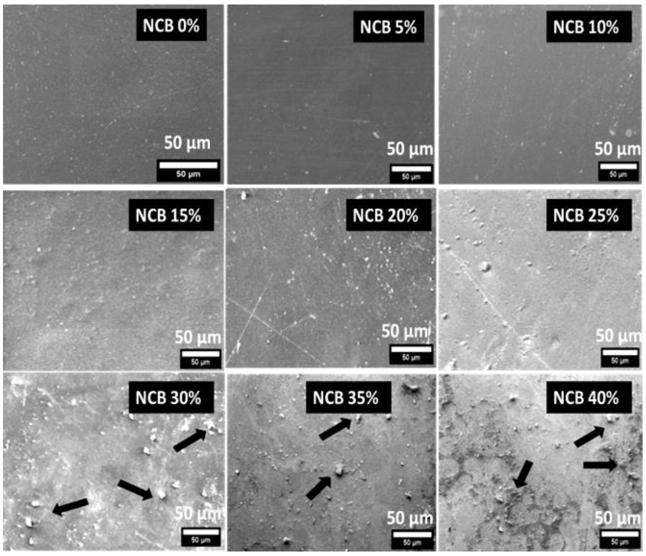

Fig. 5: Scanning electron micrograph (X1000) of pure resin and composite bipolar plates below and above percolation threshold of NCB.

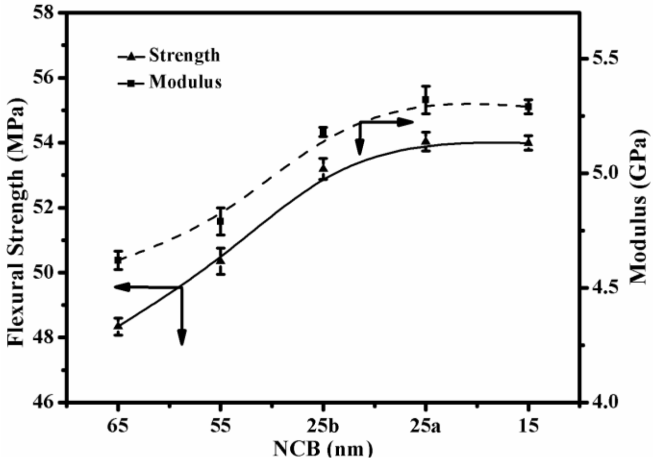

Fig. 6: Effect of NCB particle size on the flexural strength and modulus of the composite plates.

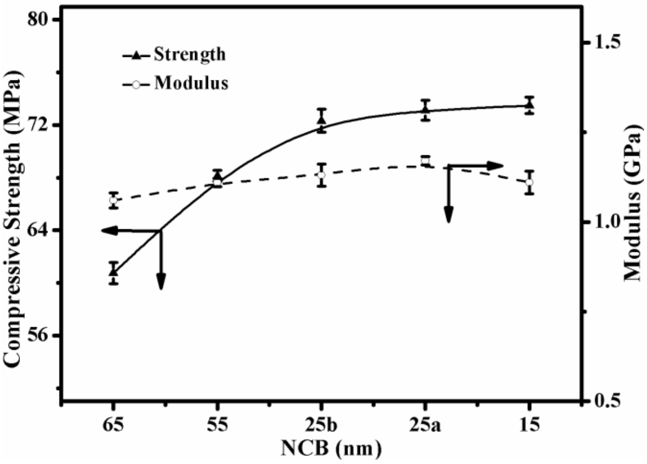

Fig. 7: Effect of NCB particle size on the compressive strength and modulus of composite plates.

Likewise, the maximum of compressive strength and modulus are 73.23 MPa and 1.12 GPa for NCB with particle size of 15 nm, and the minimum are 60.55 MPa and 1.05 GPa for NCB with particle size of 65 nm. All the composite plates prepared with five different grades of NCB exhibit superior mechanical properties in compared to DOE targets.

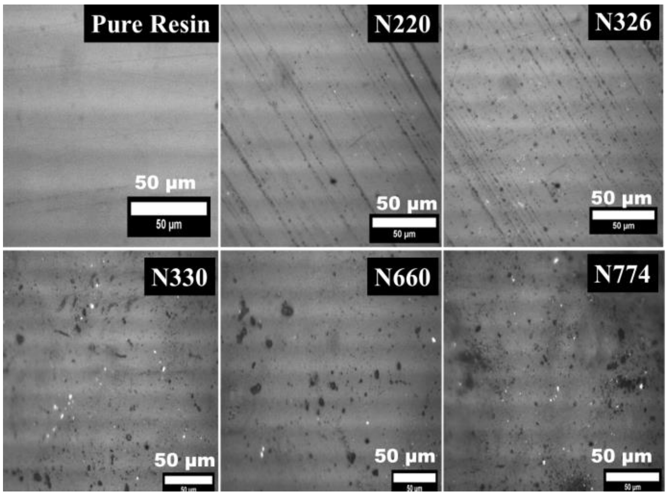

Fig. 8: Optical micrographs of pure resin and composites surfaces prepared with smaller (N220) and larger (N774) particle size (1000 X).

3.3 Surface Hardness of Carbon/Phenolic Resin Composite Bipolar Plates

The hardness measurement is a non-destructive testing, which provides surface hardness of plates at microscopic level. Here, all composite bipolar plates have been characterized by Vickers microhardness. Microhardness measurement of samples has been made with a Vickers indenter at a loading of 200g for a dwell time of 10s. Three indentations have been made on each composite's surface. Fig. 9 shows the variation in surface hardness with increasing NCB content. The surface hardness of composite plates increases with increasing NCB content from 5 to 40 wt%.

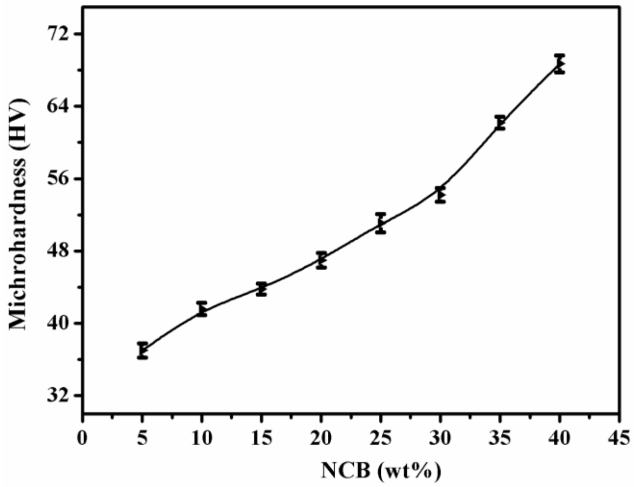

Fig. 9: Variation in surface hardness with increasing NCB content.

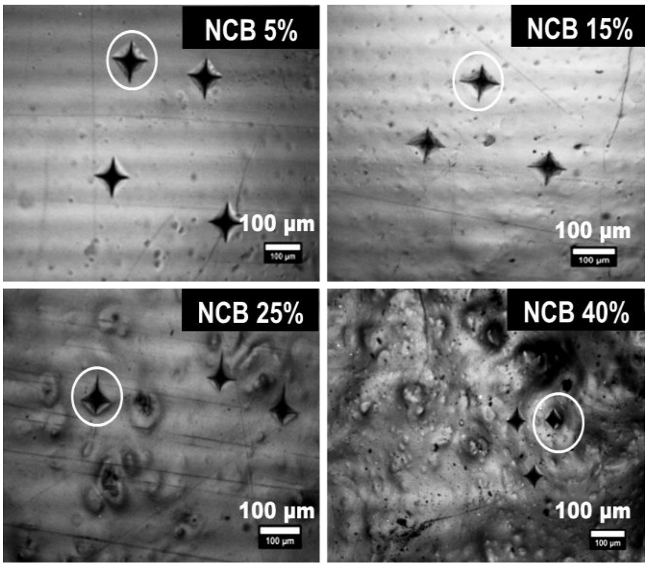

Fig. 10: Optical micrograph of composite bipolar plates showing the variation in indenter size with increasing NCB content.

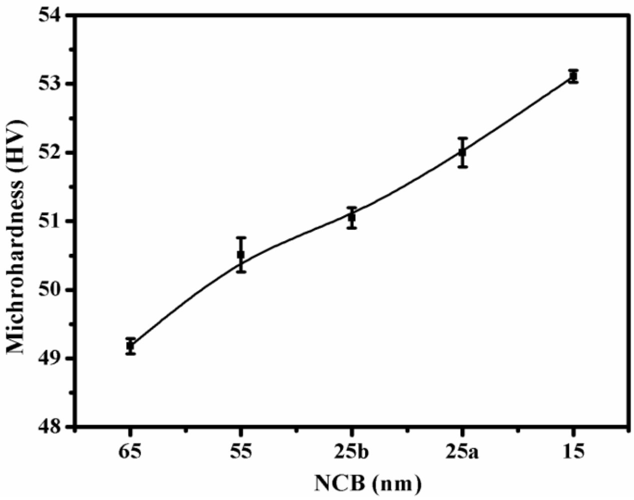

Fig. 11: Effect of NCB particle size on the surface hardness of the composite plates.

The maximum hardness observed is 66 HV at 40 wt% NCB content. It is assumed that the addition of NCB content increases the hardness of composite plates. The surface hardness of the composite is influenced by the higher hardness of NCB particles compared to resin. Moreover, the relatively uniform distribution of NCB particles and the decrease in their inter-particle distance with increasing NCB content results in increase of resistance to indentation of composites. Fig. 10 shows that as NCB content increases the size of indentation decreases, which reveals an increase in surface hardness with increasing NCB content. Furthermore, the NCB particles resist the penetration of indenter more strongly than the resin, which results an increase of surface hardness. Fig. 11 shows the variation in surface hardness of composites with decreasing NCB particle size. The hardness increases from 49.18 to 53.11 HV as NCB particle size decrease from 65 nm to 15 nm. The composite plates are induced with small size NCB particles, which have higher surface area than larger NCB particles, have stiffer composite's surface due to the stronger interaction between carbon filler and phenolic resin. Hence, composites loaded with small size NCB exhibit more hardness in comparison to composites loaded with large size NCB particles.

3.4 Dynamic Mechanical Analysis of Carbon/Phenolic Resin Composite Bipolar Plates

The dynamic mechanical analysis (DMA) has been performed to evaluate the dynamic mechanical properties of NCB reinforced phenolic composites. The measurement has been done over a temperature range of 30-270^{o}C. Figures 12, 13 and 14 show the plots of storage modulus (E'), tanδ and glass transition temperature (T_g) against temperature for all composite bipolar pates. The storage modulus provides a measure of energy stored by the material elastically and dissipates as heat is characterized as loss modulus. The damping factor (tanδ) is a measure of relative contributions of elastic and viscous components in composites. From figures, it can be observed that when the composite plates are heated up through the glass transition (T_g) region, the E' decreases rapidly, whereas tanδ reaches up to their maximum value. The results reveal that below T_g, the storage modulus has been found to increase from 1.4 to 3.4 GPa with increasing NCB content from 5 to 25 wt%. However, it has been observed that the storage modulus decreases for higher concentrations (i.e., for 30 to 40 wt%) of NCB content due to agglomeration of NCB particles and formation of micro-voids. The increase in storage modulus is due to the stiffening effect of NCB i.e., NCB can improve the stiffness of composites and provides better crosslinking between NCB particles and phenolic resin.

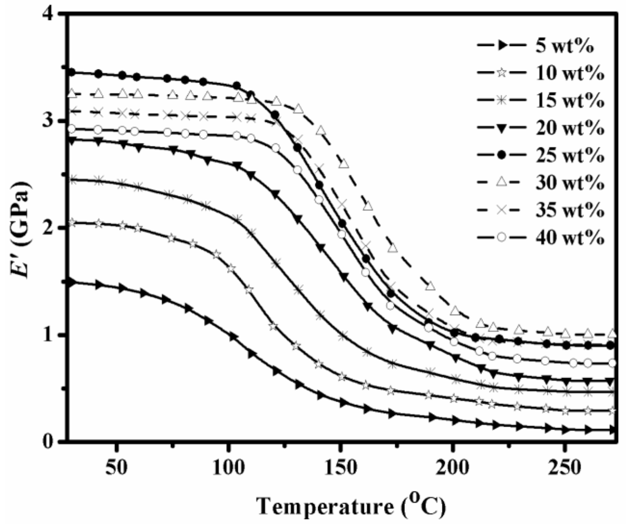

Fig. 12: Variation of the storage modulus as a function of temperature with increasing NCB content.

Fig. 13 shows the tanδ plot of all composite plates. From this figure it has been observed that the tanδ peak is shifted along the higher temperature with the addition of NCB. The increase in NCB concentration in polymer matrix restricts the movement of polymeric chains, which decreases the damping characteristics of the corresponding phase and thus reduces the tanδ. The T_g of composite increases with increasing NCB content as shown in Fig. 14. This increase in T_g is due to the stronger filler matrix interfacial bonding, which restricts the mobility of polymeric chains and pushes the transition limits towards the higher temperature. However, the T_g decreases for higher NCB concentration. This is due to the agglomeration of nanoparticles and weak interfaces at higher loading.

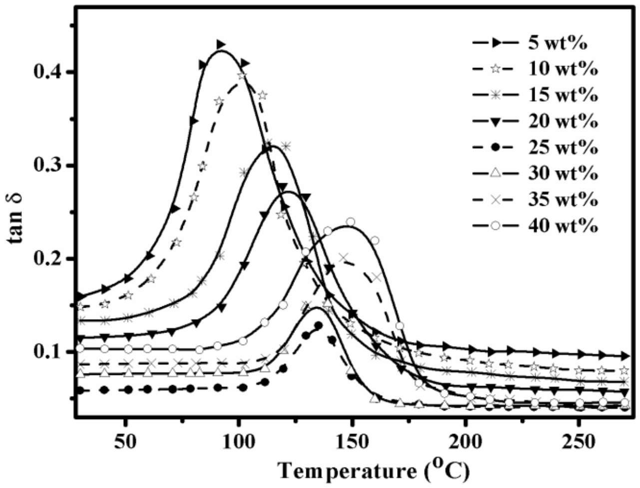

Fig. 13: Variation in tan δ as a function of temperature with increasing NCB content.

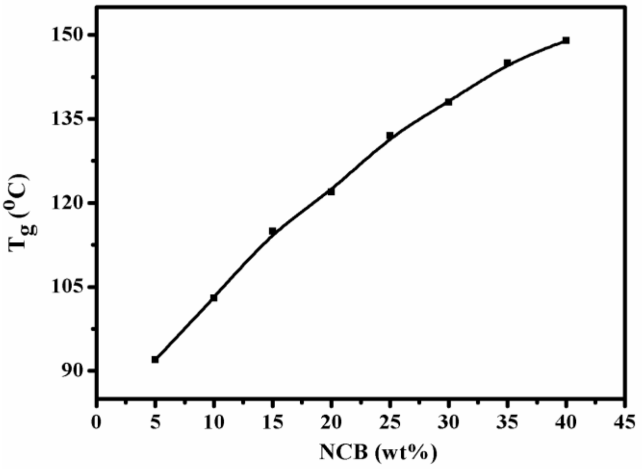

Fig.14: Variation in glass transition temperature (T_g) as a function of temperature with increasing NCB content.

Furthermore, the DMA has been employed on the composites prepared varying NCB particle sizes. Fig. 15 shows the plot of E'. The composites reinforced with small size NCB particles shows higher E' which keeps on decreasing with increasing particles size of NCB. However, in the operating temperature range of fuel cell (80-100^{o}C), the E' of the composite decrease from 4.7 to 2.6 GPa with increase in the NCB particle size from 15 to 65 nm. This attributes to the decrease in overall surface area of NCB particles with increasing particle size, which provides weak interaction between carbon fillers and phenolic resin. Small size NCB particle facilitates more surface area for the matrix compared to larger particle, which delivers better adhesion between NCB particles and phenolic resin, and provides higher *E*'.

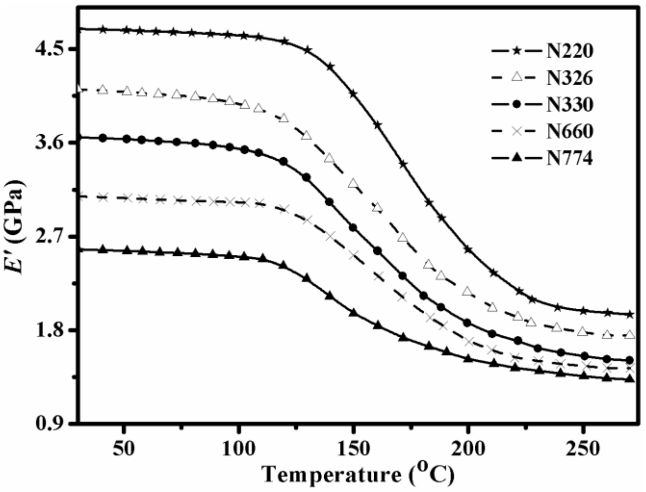

Fig. 15: Effect of NCB particle size on the storage modulus (E') of composite plates.

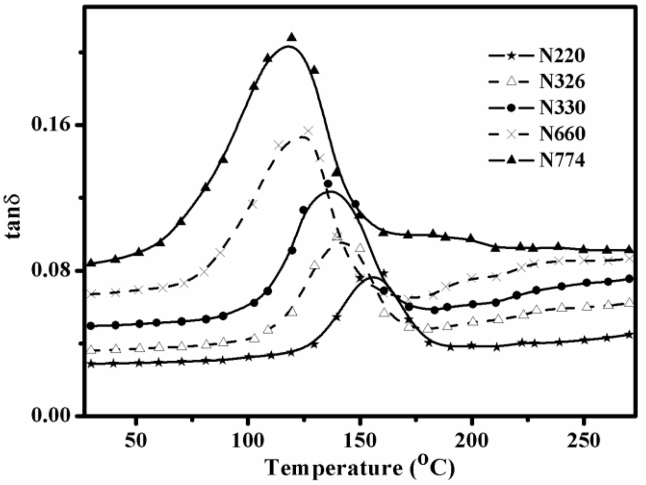

Fig. 16: Effect of NCB particle size on the tanδ of composite plates.

Fig. 16 shows the tanδ plots of all composite plates. It can be observed that the tanδ$_{max}$ peak is shifted from higher to lower value with decreasing NCB particle size, i.e., from 65 to 15 nm in the resin matrix. This is due to the fact that the smaller size NCB particles possess more surface area and thus increase the interaction between polymer chains and carbon fillers. Hence, the movement of polymer chains is reduced, and only small amount of energy could be transferred to the resin molecules, which decreases the damping characteristics of the corresponding phase and thus reduces the tanδ$_{max}$. Additionally, the T_g of composite plates is somewhat shifted towards its lower temperature with increasing particle size of NCB as shown in Fig. 17. The decrease in the T_g with increasing particles size is supposed to be due to the reduced filler-matrix interaction. It is suggested that, the inclusion of NCB with larger particle size causes induced inhomogeneity in resin matrix as shown in Fig. 8. This means that the apparent homogeneity decreases with increasing filler sizes. Hence, the unrestricted mobility of polymer chains results in reduction of T_g with increasing fillers size. Furthermore, the dispersion of NCB particle in matrix decreases with increasing NCB particle size, which results in agglomeration of NCB particles in composites, hence T_g shifts towards the lower temperature.

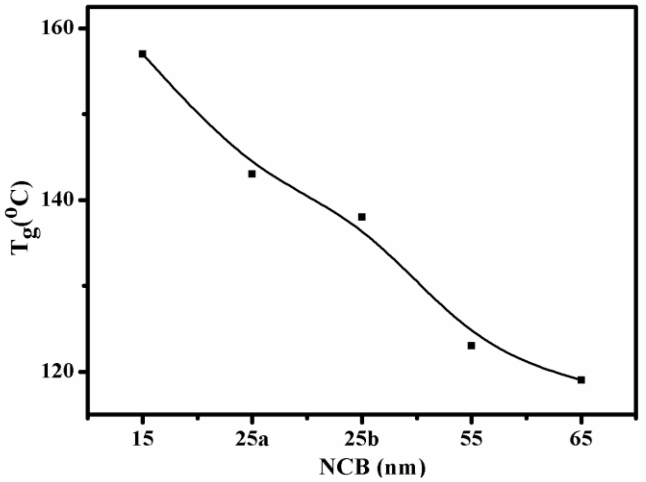

Fig. 17: Effect of NCB particle size on T_g of composite plates.

3.5 Electrical Conductivity of Carbon/Phenolic Resin Composite Bipolar Plates

The overall conductivity of the composite bipolar plates increases with increasing NCB content as shown in Fig. 18. The maximum electrical conductivity obtained is 45X10^{-2} S.cm^{-1} for 40 wt% of NCB content, which is very low in comparison to DOE target of 100 S.cm^{-1}. Electrical conductivity depends upon the conductive path through which the electron can flow easily. Here, the low electrical conductivity is observed due to the highly insulating nature of phenolic resin (10^{-12} S.cm^{-1}). The increase in conductivity with increase in NCB content is due to the formation of conducting path or decrease in the contact distance between the NCB particles. Furthermore, at higher concentrations of NCB, the homogeneously mixed NCB particles increase the number of conducting channels, which enhance the overall conductivity of the composite plates.

On the other hand, electrical conductivity increases with the increasing NCB particles size is shown in Fig. 19. The electrical conductivity of composites samples increases from 16 X 10^{-2} to 73 X 10^{-2} S cm^{-1} with increasing particle size of NCB, i.e., from 15 to 65 nm. This can be explained on the basis of contact resistance between the filler particles in the phenolic resin. The contact resistance between NCB particles highly influences the electrical conductivity of composite. The total number of the NCB particles, in composite, decreases with the increasing particle size. Hence, larger particles facilitate more contact area compared to smaller ones, which helps in making less contact resistance and provides significantly more electrical conductivity. However, the electrical conductivity for all composites is quite low in comparison to DOE target of 100 S.cm^{-1}.

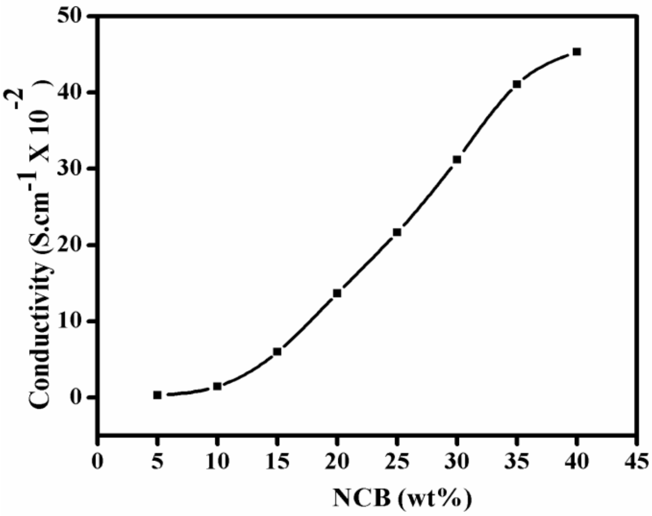

Fig. 18: Variation in electrical conductivity with increasing NCB content.

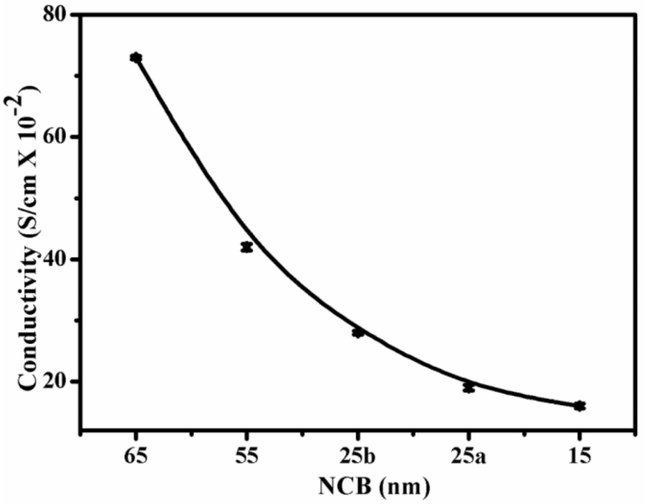

Fig. 19: Effect of NCB particle size on the electrical conductivity of the composite plates.

3.6 Thermal Stability of Carbon/Phenolic Resin Composite Bipolar Plates

Thermal stability of bipolar plates is an important parameter to decide the performance of PEM fuel cells. Therefore, the thermal stability of composite bipolar plates with respect to variation of NCB content and variation in particle sizes has been examined by TGA in a nitrogen atmosphere. Fig. 20 shows the thermo-gravimetric curves of composite bipolar plates. The TGA test for all composite plates has been carried out from 30 to 700°C, and till 300°C no significant weight loss has been observed i.e., all these composite plates are highly stable till 300°C as shown in figure. The PEM fuel cell operating temperature is about 80-120°C, hence these composite plates show a good thermal stability over the operating temperature range of fuel cell. TGA curves show that the composite plates start degrading at 280°C with 1.2 % weight loss. Major weight loss in all composite plates appears at higher temperature, which starts after 450°C and continues till 700°C.

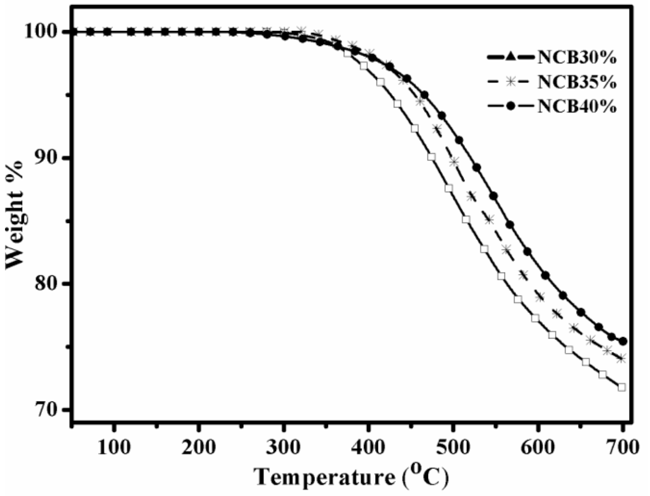

Fig. 20: TGA profiles of composites bipolar plates.

Table II shows the characteristic temperatures of the composite plates at 80 % weight loss. It has been observed that the characteristic temperature increases with increasing NCB content, which indicates that the incorporation of NCB in polymer resin improves the thermal stability of the composite bipolar plates.

TABLE II: CHARACTERISTICS TEMPERATURES AT 80% WEIGHT LOSS OF THE COMPOSITE BIPOLAR PLATES

Sample	NCB25%	NCB35%	NCB40%
Temperature (°C)	560	590	620

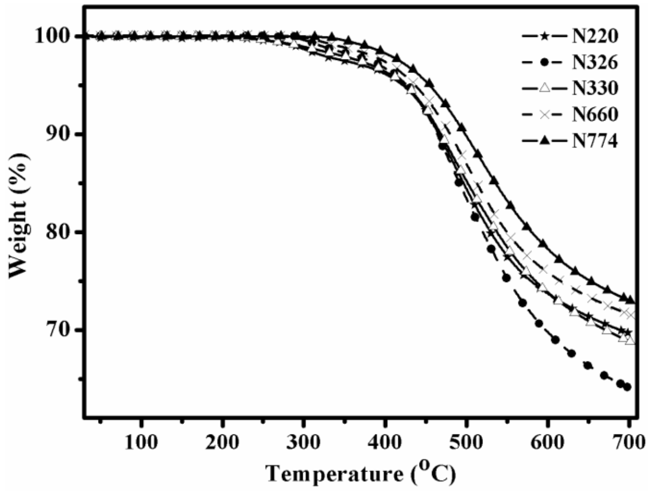

Fig. 21: Effect of carbon black particle size on the thermal stability of the composite plates.

Fig. 21 shows the thermo-gravimetric curves of bipolar plates containing five grades of NCB. The particle size variation does not show any change in thermal stability up to 280°C for all composite plates. However, TGA curves show that the composite plates start degrading at 280°C with 1.2 to 1.4 % weight losses. Major weight loss for all composite plates appears at higher temperatures, which start after 450°C and continue till 700°C.

4.7 CONCLUSION

In this study it has been observed that all of the properties under scrutiny increases with increasing

NCB concentration in resin except density. The composite bipolar plate having 25 wt% of NCB yields better properties. The plates exhibit good mechanical properties and surface hardness. Through the DMA test it has been observed that the storage modulus and T_g increase with increasing NCB content. The thermal stability shows 0.8% weight loss at 280°C i.e., the plates are thermally stable upto 280°C. This deems that the plate is suitable for PEMFC application. However, the electrical conductivity results reveal that these plates possess a low electrical conductivity of 45 X 10^{-2} S cm^{-1}. On the other hand, the composite bipolar plates prepared with five grades of NCB (25 wt%) shows that the variation of NCB particle size greatly influences all the properties of composites. The electrical conductivity of the composite plates increases from 16 X 10^{-2} to 73 X 10^{-2} S.cm^{-1} and the hardness decreases from 49 to 53 HV as NCB particle size increases from 15 to 65 nm. Furthermore, the flexural strength increases from 48 to 53 MPa and compressive strength increases from 60 to 73 MPa with decreasing the particle size. The DMA test showed that the storage modulus and T_g increases, whereas the loss modulus and tanδ decreases with increasing particle size. The thermal stability shows that the particle size variation does not show any remarkable change in thermal stability up to 280°C for all composite plates. All the composite plates show 0.6 to 0.9 % weight loss at 280°C i.e., the plates are thermally stable upto 280°C, this deems that the plates are suitable for PEMFC application. The composite plates prepared in this work exhibit excellent property in comparison to DOE targets except electrical conductivity, which is due to highly insulating nature of phenolic resin and low electrical conductivity of NCB particles. Hence, further studies would focus to enhance the electrical conductivity of these composite plates.

ACKNOWLEDGEMENT

The authors acknowledge the financial support provided by Indian Space Research Organization, India for carrying out this work.

REFERENCES

[1] Kyungmun Kang, Sunghyun Park, Hyunchul Ju, Effects of type of graphite conductive filler on the performance of a composite bipolar plate for fuel cells, Solid State Ionics 262 (2014) 332–336.

[2] Salernitano E, Giorgi L and Makris T D. Direct growth of carbon nanofibers on carbonbased substrates as integrated gas diffusion and catalyst layer for polymer electrolyte fuel cells. Int J Hydrogen Energy 2014; 39: 15005-15016.

[3] Minkook Kim, Jun Woo Lim, Ki Hyun Kim, Dai Gil Lee, Bipolar plates made of carbon fabric/phenolic composite reinforced with carbon black for PEMFC, Composite Structures 96 (2013) 569-575.

[4] Jun Woo Lim, Minkook Kim, Young Ho Yu, Dai Gil Lee,Development of carbon/PEEK composite bipolar plates with nano-conductive particles for High-Temperature PEM fuel cells (HT-PEMFCs), Composite Structures 118 (2014) 519–527.

[5] Steele BCH and Heinzel A. Materials for fuel-cell technologies. Nature 2001; 414: 345-352.

[6] F. A. de Bruijn, V. A. T. Dam, and G. J. M. Janssen, Review: Durability and Degradation Issues of PEM Fuel Cell Components, Fuel Cells 08, 2008, 3–22.

[7] Anne-Claire Dupuis, Proton exchange membranes for fuel cells operated at medium temperatures: Materials and experimental Techniques, Progress in Materials Science 56 (2011) 289–327.

[8] Satish G. Kandlikar *, Zijie Lu, Thermal management issues in a PEMFC stack-A brief review of current status, Applied Thermal Engineering 29 (2009) 1276–1280.

[9] Bashyam R and Zelenay P. A class of non-precious metal composite catalysts for fuel cells. Nature 2006; 443: 63-66.

[10] G. Hinds and E. Brightman, Towards more representative test methods for corrosion resistance of PEMFC metallic bipolar plates, International Journal of Hydrogen Energy, 40 (2015) 2785-2791.

[11] Minkook Kim, Jun Woo Lim, Ki Hyun Kim, Dai Gil Lee, Ultra high speed curing bipolar plates made of carbon fabric/phenolic composite using acid catalyst for proton exchange membrane fuel cell, Composite Structures 108 (2014) 1–8.

[12] Ki Hyun Kim, Jaeheon Choe, Soohyun Nam, Bu Gi Kim, Dai Gil Lee, Surface crack closing method for the carbon composite bipolar plates of a redox flow battery, Composite Structures 119 (2015) 436–442.

[13] Jun Woo Lim, Minkook Kim, Dai Gil Lee, Conductive particles embedded carbon composite bipolar plates for proton exchange membrane fuel cells, Composite Structures 108 (2014) 757–766.

[14] M. A. Deyab, Corrosion protection of aluminum bipolar plates with polyaniline coating containing carbon nanotubes in acidic medium inside the polymer electrolyte membrane fuel cell, Journal of Power Sources 268 (2014) 50-55.

[15] Lee HS, Kim HJ, Kim SG, Ahn SH. Evaluation of graphite composite bipolar plate for PEM (proton exchange membrane) fuel cell: electrical, mechanical, and molding properties. J Mater Process Technol 2007;187:425–8.

[16] Hermann A, Chaudhuria T, Spagnol P. Bipolar plates for PEM fuel cells: a review. J Hydrogen Energy 2005; 30:1297–302.

[17]Petrach E, Abu-Isa I and Wang X. Synergy Effects of Conductive Fillers on Elastomer Graphite Composite Material for PEM Fuel Cell Bipolar Plates. J Compos Mater 2010, 44: 665-1676.

[18]Chul Kyu Jin, Ja Yoon Koo, Chung Gil Kang, Fabrication of stainless steel bipolar plates for fuel cells using dynamic loads for the stamping process and performance evaluation of a single cell, International Journal of Hydrogen Energy 39 (2014) 21461-21469.

[19]S. Pugal Mani, A. Srinivasan, N. Rajendran, Effect of nitrides on the corrosion behavior of 316L SS bipolar plates for Proton Exchange Membrane Fuel Cell (PEMFC), International Journal of Hydrogen Energy 40 (2015) 3359-3369.

[20]Nen-Wen Pu, Gia-Nan Shi, Yih-Ming Liu, Xueliang Sun, Jeng-Kuei Chang, Chia-Liang Sun, Ming-Der Ger, Chun-Yu Chen, Po-Chiang Wang, You-Yu Peng, Chia-Hung Wu, Stephen Lawes, Graphene grown on stainless steel as a high-performance and ecofriendly anti-corrosion coating for polymer electrolyte membrane fuel cell bipolar plates, Journal of Power Sources 282 (2015) 248-256.

[21]Ling Du, Sadhan C. Jana, Highly conductive epoxy/graphite composites for bipolar plates in proton exchange membrane fuel cells, Journal of Power Sources 172 (2007) 734–741.

[22]E. Middelman, W. Kouta, B. Vogelaar, J. Lenssen, E. de Waal, Bipolar plates for PEM fuel cells, Journal of Power Sources 118 (2003) 44–46.

[23]Joong Hee Lee, Yun Ki Jang, Chang Eui Hong, Nam Hoon Kim, Peng Li, Hong Ki Lee, Effect of carbon fillers on properties of polymer composite bipolar plates of fuel cells, Journal of Power Sources 193 (2009) 523–529.

[24]Renato A. Antunesa, Mara C.L. de Oliveira, Gerhard Ett, Volkmar Ett, Carbon materials in composite bipolar plates for polymer electrolyte membrane fuel cells: A review of the main challenges to improve electrical performance, Journal of Power Sources 196 (2011) 2945–2961.

[25]Sie Chin Tjong, Polymer nanocomposite bipolar plates reinforced with carbon nanotubes and graphite nanosheets, Energy Environ Sci 2011, 4, 605.

[26][19] Joong Hee Lee, Jin-Sun Lee, Tapas Kuila, Nam Hoon Kim, Daeseung Jung, Effects of hybrid carbon fillers of polymer composite bipolar plates on the performance of direct methanol fuel cells, Composites: Part B 51 (2013) 98–105.

[27]Reza Taherian, Mohammad Jaffar Hadianfard, Ahmad Nozad Golikand, Manufacture of a polymer-based carbon nanocomposite as bipolar plate of proton exchange membrane fuel cells, Materials and Design 49 (2013) 242–251.

[28]Reza Taherian, A review of composite and metallic bipolar plates in proton exchange membrane fuel cell: Materials, fabrication, and material selection, Journal of Power Sources 265 (2014) 370-390.