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Original Research Paper

Enhanced thermo-mechanical and electrical properties of carbon-carbon composites using human hair derived carbon powder as reinforcing filler

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A B S T R A C T

In the present study, human hair derived carbon powder (HHC) synthesized in home laboratory is characterized via SEM, AFM, FT-IR, XRD, Raman, XPS, and TGA. Then HHC is used as a low cost reinforcing filler at 0–50 wt% with phenolic resin for fabricating carbon fabric reinforced polymer composites (CPCs) and its carbon-carbon composites (CCs). CPCs are fabricated via simple hand-lay techniques for resin-HHC slurry impregnation followed by hot pressing while CCs are obtained by carbonization of CPCs at 600 and 900 °C. Effects of HHC loading on CPCs and CCs are evaluated through static and dynamic mechanical thermal analysis, density, electrical conductivity, morphology, and microstructure studies. Tensile and flexural properties (strength and modulus) of CPCs and CCs improve significantly (~25 to 73%) at 30 wt% HHC loading. Storage modulus (E′) and loss modulus (E″) of CPCs increase up to 132 and 104%, respectively with addition of HHC up to 40 wt%. E′ and E″ of unfilled CCs increase with carbonization temperature, however they decrease with increasing HHC content. In addition to high specific properties, CCs also exhibit substantial increment (~233%) in electrical conductivity and thermal stability, which make HHC one of the most suitable material for high temperature-structural applications.

1. Introduction

Carbon-carbon composites (CCs) possess unique combination of properties like very high specific strength and stiffness, excellent resistance to ablation and corrosion, very low coefficient of thermal expansion, high specific thermal conductivity and good tribological properties [1–4]. Hence, these composites are currently employed in high performance applications such as thermal protection system of wing leading edges of aircraft, nose cap of the space shuttle, plasma facing components of nuclear power plants, heat shields for space re-entry vehicles also their ablative applications such as missile nose tips and rocket nozzle throats, and moreover their friction applications such as aircraft and racing cars brake discs and clutches. Owing to the biocompatibility and inertness, they are also used in fabrication of medical devices such as surgical tools, etc. [1,5,6].

The CCs are generally manufactured either by high temperature carbonization followed by graphitization of carbon reinforced polymer composite preform (green composite) in an inert atmosphere or by pyrolytic-carbon matrix precursor obtained from pyrolysis/chemical vapour infiltration (CVI) at high temperature and moderate pressure of hydrocarbon gases or liquids in the carbon fibre preform [2,7,8]. The polymer based composite preforms/precursors are fabricated by impregnation of liquid polymer resin (mainly thermosetting type such as epoxy or phenolic, or thermoplastic type such as pitch, PEEK) into carbon fibre (prepreg) followed by curing (with or without catalyst) by application of specific cure cycle of temperature and pressure. The CCs formed after carbonization is actually a porous solid structure with very low density and poor mechanical properties as results of the removal of organic gases and other volatile matters with simultaneous reduction in weight, shrinkage and more cracks in the resin matrix [9,10]. Hence, in order to increase density (or reduce porosity), CCs are subjected to cyclic densification process until the composites become almost nonporous and its density touches the design standard value for specific applications. This densification process is generally done either by repeated resin impregnation followed by carbonization of the precursor polymer composites or by gas phase CVI of precursor composite. These processes are very time consuming and also involve huge capital investment

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and required technical expertise, which limit their application mainly in defence and aerospace sector [11–13].

In order to amplify the scope of applications of CCs, some of the research groups have concentrated their research work on cost reduction of the CCs by modification in the formulations/raw materials compositions used in the manufacture of the precursor polymer composites. Consequently, they have used various forms of carbon fillers such as micro and meso carbon beads [14], vapour grown carbon fibres [15], micro and nanostructured carbon black [16,17], and graphite powder [18,19], in the polymer resin matrix. It has been revealed that on addition of any one of these nanostructured fillers in the polymer matrix, reduces the shrinkage and cracks during carbonization of carbon phenolic composites (CPCs), also change in microstructure from non-graphitic to graphitic carbon, which ultimately results in significant improvement in mechanical strength, stiffness and fracture strength of CCs. It has also been observed that the loading of silicon carbide (SiC) and graphite fillers in the carbon matrix improve the wear resistance and thermal conductivity and electrochemical properties of CCs [19–21]. More recently, Dae et al. have found that the carbon nanotubes (CNTs) can be used to improve the tribological properties of CCs [22]. CNTs can also be used to enhance density and mechanical strength of the CCs [23,24]. Nanographene platelets exhibit low viscosity in its polymer composites and also have high heat of curing, hence it can be a good filler for crack filling and densification of the CCs [25]. Although the researchers have achieved the satisfactory level of density and improved mechanical, electrical and other properties in fewer steps of densification cycle process, however, the actual change in the properties of the particulate filled composites depends on the particle structure or shape, size interfacial adhesion between filler and resin, and relative amount of filler and reinforcements and resin used in the composites [26–28]. Herein, most of the fillers used are difficult to synthesis and costly and moreover obtained from non-renewable resources, which may ultimately result in costly product of CCs and this also increases the depletion of fossil reserves. Hence, the researchers are striving hard to find the alternate of these carbon fillers from naturally and abundantly available resources. Recently, the researchers have focused their work on the synthesis and applications of various forms of carbon nano-structured materials such as CNTs and graphenes, which can be derived from organic wastes available naturally free of cost such as food and agricultural wastes, wood wastes, animal bones, silks waste, human hair, etc., in order to save the limited reserve of fossil fuels [29].

The waste human-hair available abundantly and free of cost from the barber's shop. It is basically made up of more than 90% proteins (polypeptides), contain more than 50% carbon, ~25% oxygen, ~17% nitrogen, ~6% hydrogen, ~4% sulphur and traces of other minerals [29]. Owing to the unique chemical composition and attractive combination of properties such as high elastic properties, high strength, high thermal insulation characteristic, biocompatibility etc., the waste human hair has become an interesting material for various sectors of research and industries [30,31]. The burned human hair has porous structure, therefore it can be used as a selective metal adsorbent for removal of metal ion impurities from aqueous metals ions solutions [32].

Human hair derived carbon powder (HHC) is also used as a source of nitrogen and other minerals in fertilizers. It has inherent doping of nitrogen and sulphur, which can be used as gas adsorption application [33,34]. It has also been employed as the carbon flake in fabrication of electrochemical supercapacitors [35]. The HHC micro fibre can be used to fabricate chemical sensing devices [36]. It is worth to mention that as HHC has very porous structure, high surface area and light weight, it seems to be useful as filler material to increase density, mechanical as well as thermal properties of the CCs. But the actual effects are still the subject of research. Unfortunately, there is no such study of this kind, available in open literature. Hence, in order to address these aforesaid problems, in the present work, phenolic-carbon fabric composites are manufactured having 0–50 wt% of HHC filler with respect to phenolic resin under similar processing conditions and then carbonized in an inert atmosphere at different heat treatment temperatures for making CCs. In this study, CPCs are prepared without and with different wt% loading of HHC under the same processing conditions. The effects of the HHC loading on the viscoelastic properties of the composites have investigated by the dynamic thermal analysis (DMTA) [37–40]. Herein, viscoelastic properties such as storage modulus, loss modulus, damping factor are discussed. These properties are also correlated with the other controlling parameters like entanglement density [41], reinforcement efficiency [42], adhesion factor [42], b factor [42] and C factor [43]. As these factors play important role to determine the processability of HHC-polymer composites at large scale and also helpful to evaluate the reinforcement efficiency carbon fillers like HHC and the structural stability of the polymer composites as well as CCs [39–44]. The effects of HHC loading on the static mechanical properties of the composites are also studied through tensile strength (TS), Young's modulus (YM), strain at failure, flexural strength (FS) and flexural modulus (FM), laminate thickness, bulk density and also electrical conductivity of the CPCs as well as CCs.

2. Experimental

2.1. Materials

The matrix material used in this work was phenolic resin (ABRON PR100-WS) supplied by M/S ABR Organics, India. The specific gravity and volatile content of the resin were 1.12–1.15 and 32–39%, respectively. The reinforcement material used to fabricate CPCs and their CCs was bi-directional plain weave PAN based carbon fabric, which was supplied by M/S Zoltek Corporation, USA. The filament diameter, density, TS and YM of the carbon fibres were 7.2 μm, 1.81 g/cc, 3860 MPa and 242 GPa, respectively. The filler used in the fabrication of these composites is waste human hair derived carbon (HHC) with bulk density of 1.25 g/cc, which was processed in the home laboratory.

2.2. Synthesis of human hair derived carbon powder (HHC)

HHC was derived from after processing waste human hairs via collecting, sorting, chopping in small pieces, washing with deionized water, drying at 65 °C for 4 h and then carbonization process. The carbonization of human hair was done at 500 °C in the horizontal quartz tubular furnace with the nitrogen environment and constant heating rate of 5 °C/min. The flow rate of nitrogen gas was kept at ~100 CC/min throughout the process. After the carbonization process, the tube was left for cooling overnight under nitrogen environment, thereafter the carbonized HHC sample was grinded to fine powder with the help of mortar and pestle for characterization.

2.3. Composites fabrication

In this study, CPCs were used as green composites (preforms) to fabricate CCs. CPCs with and without HHC filler were fabricated by conventional hand lay-up technique followed by curing in a hot press. Initially measured amount of as received phenolic resin was mixed with 0–50 wt% HHC filler (with increment of 10 wt%) in a glass beaker using a magnetic stirrer operated at 300 rpm for 30 min to make slurry, which was then impregnated in the carbon fabric. HHC used as filler material, was obtained by carbonization