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Applications of Carbon Fibers Produced from Polyacrylonitrile Fibers

R. Eslami Farsani, R. Fazaeli

***Abstract*—**Carbon fibers have specific characteristics in comparison with industrial and structural materials used in different applications. Special properties of carbon fibers make them attractive for reinforcing and fabrication of composites. These fibers have been utilized for composites of metals, ceramics and plastics. However, it's mainly used in different forms to reinforce lightweight polymer materials such as epoxy resin, polyesters or polyamides. The composites of carbon fiber are stronger than steel, stiffer than titanium, and lighter than aluminum and nowadays they are used in a variety of applications. This study explains applications of carbon fibers in different fields such as space, aviation, transportation, medical, construction, energy, sporting goods, electronics, and the other commercial/industrial applications. The last findings of composites with polymer, metal and ceramic matrices containing carbon fibers and their applications in the world investigated. Researches show that carbon fibers-reinforced composites due to unique properties (including high specific strength and specific modulus, low thermal expansion coefficient, high fatigue strength, and high thermal stability) can be replaced with common industrial and structural materials.

***Keywords*—**Polyacrylonitrile Fibers, Carbon Fibers, Application

I. Introduction

WITHOUT considering gold and silver fibers which are special, expensive and have limited applications, carbon fibers are first manmade fibers which have found wide applications in industries. Today after 100 years of first carbon fibers applications, these fibers are still special synthetic fibers with widespread applications. Carbon fibers have been made inadvertently from natural cellulosic fibers such as cotton or linen for thousands of years. However, it was Edison who, in 1878, purposely took cotton fibers and later, bamboo, and converted them into carbon in his quest for incandescent lamp filaments. Interest in carbon fibers was renewed in the late 1950s when synthetic rayon in textile form was carbonized to produce carbon fibers for high-temperature missile applications [1-3].

At the end of the 1960s, carbon fibers based on polyacrylonitrile (PAN) were developed in Japan and appeared in the commercial market. Research aimed at obtaining partially carbonized and carbon fiber based on PAN fibers started for the first time (1959-1960) in the USSR, before the Japanese investigation. However, at that time, the results were not brought into practical application. The first pitch-based carbon fiber was developed by Otani in Japan using polyvinyl chloride (PVC) pitch as the raw material9. In recent years, this fiber has been produced from vapor-grown, but it is still in the experimental stage [4-7].

R. Eslami Farsani is with South Tehran Branch, Islamic Azad University, Tehran, Iran (corresponding author to provide phone: 98-21-88303278; fax: 98-21-88830012; e-mail: R_eslami@azad.ac.ir).

R. Fazaeli is with South Tehran Branch, Islamic Azad University, Tehran, Iran (e-mail: R_fazaeli@azad.ac.ir).

Nowadays, the common method for industrial production of carbon fibers is pyrolysis of organic materials. To produce carbon fibers by solid state pyrolysis of organic materials, different polymers are used as a precursor. This process is accompanied by weight loss from evolution of non-carbon elements, polymer heat release and molecule shape change. Finally carbon fibers with laminar and ring structures and high percentage of carbon content are obtained. Three precursors including PAN-based, rayon-based, and pitch-based fibers are mainly used for the production of carbon fibers. At present, PAN fibers are the most important and commonly used precursor for production of carbon fibers. Advantages of these fibers are high degree of directional molecule, high melting point, high productivity of carbon fibers (about 50%) and high mechanical properties and suitable price [3,8-10].

PAN fiber is a form of acrylic fiber. Acrylic fibers manufactured presently are composed of at least 85% by weight of acrylonitrile (AN) units. The remaining 15% consists of neutral and/or ionic comonomers which are added to improve the properties of the fibers. Neutral comonomers like methyl acrylate (MA), vinyl acetate (VA), or methyl methacrylate (MMA) are used to modify the solubility of the acrylic copolymers in spinning solvents, to modify the acrylic fiber morphology, and to improve the rate of diffusion of dyes into the acrylic fiber. Ionic and acidic comonomers including the sulfonate groups like sodium methallyl sulfonate (SMS), sodium 2 – methyl - 2 - acrylamidopropane sulfonate (SAMPS), sodium p-styrene sulfonate (SSS), sodium p-sulfophenyl methallyl ether (SMPE), and itaconic acid (IA) also can be used to provide dye sites apart from end groups and to increase hydrophilicity. This organic material has an open chain structure with carbon as its backbone. The molecular structure of this fiber is composed of a set of long chain molecules.

The manufacture of carbon fibers from PAN-based precursors is composed of two steps including thermal stabilization and carbonization. The first step (stabilization) involves heating the PAN fibers to approximately 180-300 ºC in an oxygen-containing atmosphere to further orient and then crosslink the molecules, such that they can survive higher temperature pyrolysis without decomposing. The chemistry of the stabilization process is complex, but consists of cyclization of the nitrile groups (C≡N) and cross-linking of the chain molecules followed by dehydrogenation and oxidative reactions. This process transforms the linear polymer (or laterally ordered polymer) into a ladder structure which renders the polymer thermally stable and prevents melting during the subsequent carbonization process. The second step involves a carbonizing heat treatment of the stabilized PAN fibers to remove the non-carbon elements in the form of different gases like H_2O, NH_3, CO, HCN, CO_2 and N_2.

Carbonization is carried out at temperatures ranging from 1000 to 1500 ºC in an inert atmosphere. During this process, the fibers shrink in diameter and lose approximately 50% in weight. An additional step after carbonization is to further heat treat the fiber at a higher graphitization temperature in order to increase the mechanical properties [9,11]. Fig. 1 shows schematic view of carbon fibers fabrication from PAN fiber.

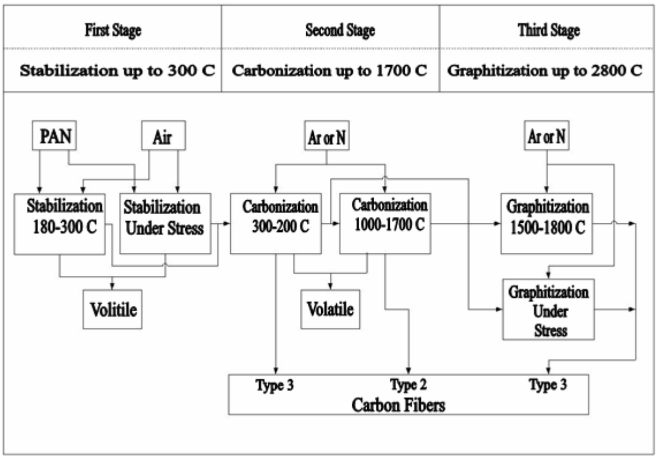

Fig. 1 Schematic representation of carbon fibers fabrication from PAN fibers

II. Applications of Carbon Fibers

Carbon fibers have specific characteristics in comparison with industrial and structural materials used in different applications. Special properties of carbon fibers make them attractive for reinforcing and fabrication of composites, but main problem in this respect is high cost of carbon fibers. These fibers have been utilized for composites of metals [12], ceramics [13] and plastics [14]. After production of different carbon fiber types, these fibers treated by complimentary processes and then are presented in to the market. In Table 1, the most important forms of carbon fibers and their applications has been described. [2,4,11,21].

TABLE I
Forms of Carbon Fibers and Major usage

Forms	Major Usage
Filament	Resin reinforcement material for CFRP, CFRTP or C/C composites, having such usage as Aircraft/ Aerospace equipment, sporting goods and industrial parts
Tow	Resin reinforcement material for CFRP, CFRTP or C/C composites, having such usage as Aircraft/Aerospace equipment, sporting goods and industrial parts
Staple Yarn	Heat Insulator, Anti-friction material, C/C composite parts
Woven fabric	Resin reinforcement material for CFRP, CFRTP or C/C composites, having such usage as Aircraft/ Aerospace equipment, sporting goods and industrial equipment parts
Braid	Resin reinforcement material particularly suitable for reinforcement of tubular products
Chopped fiber	Compounded into plastics/resins to improve mechanical performances, abrasion characteristic, electric conductivity and heat resistance
Milled	Compounded into plastics/resins or rubber to improve mechanical performances, abrasion characteristic, electric conductivity and heat resistance
Felt, Mat	Heat insulator, base material for molded heat insulator, protective layer for heat resistance and base material for corrosion-resisting filter
Paper	Anti-electrostatics sheets, electrodes, speaker-cone and heating plate
Prepreg	Aircraft/Aerospace equipment, sporting goods and industrial equipment parts needing lightness in weight and high performances
Compounds	Housing etc. of some equipment taking advantages of electric conductivity and lightness in weight

The composites of carbon fiber are used in a variety of applications like as aerospace, construction, transportation, sporting goods, and another commercial/industrial applications [15,16]. The main applications come as follow.

A. Space Industry

In space industry, materials with light weight, high specific stiffness and strength and low heat expansion coefficient are needed; therefore carbon fibers are ideal for these applications. Composites with metal matrix (Al and Mg) and with carbon fibers reinforcement are important materials which were used in space structure like international space station. Also carbon fibers composites with epoxy matrix have been used in satellites and space probes as alternative of aluminum alloys since 1970's. Additionally, many components of space shuttle and rockets like heat shield, high-pressure storage tank, stiffeners and booster case have been made from carbon or polymer composites with carbon fibers reinforcement [14,17].

B. Aviation Industry

Carbon fibers are used in aviation industries like in commercial & military planes and helicopters to reduce the weight and to increase the strength and efficiency. Brake wing components, tail and body of planes (like 737 and 747 Boeings) and rotor blades of helicopters are some of the applications of carbon fibers composites. Also in F-14 plane (produced in 1970's) more than 100 carbon fiber composite components were used. In recent years, carbon fibers reinforced polymer composites (CFRP) have been used in B777 and B767 Boeings in different components like Stabilizers, aileron, floor beams and etc. In A320, A330 and A340 Airbus planes, the composites have been used in flaps, stiffeners, wings and etc. These applications are some instances of carbon fibers composites in planes and their usage develops more rapidly [13,18].

C. Transportation

As a result of increasing attention to environmental problems, to design clean car with lowest fuel consumption has become a very important objective. To achieve the objective, car builders are making their serious efforts to develop the process to reduce car weight and fuel consumption by the use of CFRP for structural parts.

These materials are durable, lighter than metals and have high mechanical properties. Power transmission shaft, frame, diesel engine cylinder and some components of engine are some of carbon fibers applications in car industry. Today carbon fibers composites are necessary material for racing cars. Carbon Fibers are used also for compressed natural gas (CNG) tanks for natural gas cars, for hydrogen tanks installed on fuel battery cars [19,20]. Carbon fibers are used in bodies of medium and high speed ships and hovercrafts, because of sea environment resistance in and high surface quality. Today there are efforts to produce low price vehicles by using carbon fibers [20,21].

D. Medical

Carbon fibers composites can replaced instead of other biomaterials (e.g. metals, ceramics and polymers) in the many applications, because of special properties (such as light weight, similar stiffness of hard tissues, high strength, and resistance against fatigue and corrosion), compatible with the modern diagnostic methods and no negative effect on tissue [22-24]. CFRP are used in hard and soft tissues of body. These composites are used as limbs, implants, components and filler materials for replacement, supplement and fixation of body organ. Some of applications of CFRP in body are ligament, tendon, cartilage, dental post, dental bridges, skull, sterile bandage for burn, bed sore and scars, external fixator for repairing and lengthening bones and also as artificial bones and replacing pieces for different joints [22,25]. In medical equipments, CFRP are used. These composites are widely used for X-ray inspection equipment making use of its X-ray permeability. Furthermore, CFRP is used for welfare equipment such as wheelchairs, care beds and portable slope [14,21].

E. Construction

Carbon fibers have been used as infrastructure reinforcement in Japan, United States and Europe from ten years ago. Light weight, high strength and stiffness and good durability are important parameters of carbon fibers which lead them to be applied in this application. Reinforcement of concrete with short and long carbon fibers, cables for suspension bridges and as the substitute for steel frames are some of these fibers applications in construction industry. CFRP are used for improvement and strengthening of structures in the form of cloth and sheet on surfaces of beam, floor and roof of buildings and carrying beams of bridge [26-28]. In recent years carbon fibers composites are used as reinforcement of buildings against the earthquake and enhancement of weak structures (especially in Japan). Also it is predicted CFRP's are used as protecting material against the electromagnetic inferences and as intelligent material for detection of detects in structures [28,29]. Carbon fibers in structural applications can be used instead of asbestos. Cements having low percentage short carbon fibers have better elastic modulus and strength in comparison with cements reinforced by asbestos and also have less environmental problems [29].

F. Energy

Producing energy from wind is under development. In order to get more energy from wind turbine, very big blades are needed. Today CFRP are used to produce very big blades [21].

In oil industry, carbon fibers composites are used for cables supporting off-shore construction, pipes carrying oils and drilling pipes for finding oil & gas from depth of waters and difficult-to-access reserves, because these composites have light weight, high strength and fatigue resistance and durability in comparison with other materials [30,31]. Also active carbon fibers have been used for methane and natural gas storages and for recovering and recycling spilled heavy oil. These types of carbon fibers have specific surface area and high porosity; therefore it has capability of attraction and keeping of liquid or gaseous materials [31-33].

G. Sporting Goods

Because of superior performance of carbon fibers, many sporting goods have made from this material. In 1970's, fishing rods, golf shafts and tennis rackets were made from carbon fibers and gradually in other sports, carbon fibers were used. Today carbon fibers composites are considered as important and necessary material in many sporting goods such as Badminton and squash rackets, baseball bats and ski sticks [12, 14, 21].

H. Electronic

Carbon fibers added to nylon or resins by 10-60% make it possible to reduce weight of plastic parts or to reduce their thickness because of its superior mechanical performances. These composites can carrying static load and are used as a protective layer against electromagnetic interferences. Also their usage reduces the weight of housing of electronics equipment such as notebook computers and LCD projectors as well as of camera bodies and lenses [4, 21].

I. Miscellaneous

Industrial gas turbine fuel tanks, internal body of plasma chamber in fusion reactors, extraction and separation of noble metals, wear resistance components, self-lubrication bearings, disc brakes in mine elevators, gases and poisonous materials absorbant, shuttle in textile industry and usage for water purification are some other carbon fibers applications [34-36].

III. Conclusion

Carbon fibers are used as the main component of advanced composites. The main drawback for application of these fibers is high price. But because of their outstanding mechanical and physical characteristic, their applications become develop in short period of time. Studies show that regarding to different raw material for production carbon fibers and possibility of using different methods of production, the price of these fibers begins to reduce. Also in future, carbon fibers with required properties can be fabricated for each application. Therefore because of excellent properties, it seems carbon fibers are replaced with many industrial materials and in foreseeable future these fibers are considered as essential materials for most of applications.

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