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Review Article

Carbon-Carbon Composite Application Areas and Limitations

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ABSTRACT

Carbon-Carbon composites are a new class of engineering materials that are ceramic in nature but exhibit brittle to pseudo plastic behavior. Carbon fiber reinforcements when embedded in carbonaceous matrix material results in Carbon-Carbon composites. Carbon-carbon composites due to their far superior thermo-mechanical properties are used in a number of demanding applications. However, the material is still being used in specific high-tech applications with few exceptions in general industrial applications. The material is extremely expensive and the major challenge is to reduce cost by modifying the various fabrication techniques available.

This article review represents a review of some major developments in Carbon-Carbon composites including properties, major applications, and future potential. Improving structural components and elements by various techniques such as matrix reinforcements along with decreasing of manufacturing costs make this family of materials more and more attractive to a variety of engineering applications, especially high-performance applications.

Keywords: Thermo-mechanical; Fabrication techniques; Fabrication protection; Cost reduction

INTRODUCTION

Carbon-Carbon composites are those special campsites in which both the reinforcing fibers and the matrix material are both pure carbons. Carbon is a unique element that can exhibit different properties in different forms. Some forms of carbon are extremely hard, like diamond, while some forms are extremely soft and ductile. Thus, in addition to its well-defined allotropic forms (diamond and graphite), carbon can take any number of quasi-crystalline forms ranging from amorphous or glassy carbon to highly crystalline graphite [1, 2]. Carbon-Carbon Composite have some application like; hot pressed die, turbo jet engine component, heating elements and Various space structural applications. The components of Carbon-Carbon have been manufactured in the military, commercial aircraft and defense applications with High performance braking systems.

Devi, et al. [3] has mentioned that C/C composite possesses great compatibility and is antithrombotic to human body structure, blood, and skeleton, and therefore C/C composite was selected as one of biomaterials such as artificial joint, skeleton, and heart. As we previously mentioned the properties of C/C composite, the advantages of carbon/carbon composite made of carbon fiber-reinforced carbon matrix include high temperature and high elastic coefficient, low density, low-thermal-expansion coefficient and high fatigue resistance.

Background and early development

Carbon-Carbon (C-C) composites are a new class of materials made by arrangement of several components together to create a product that is stronger than the sum of their constituents. The significant usefulness of (C-C) composites comes from their high and enhanced properties compared to other materials.

The early forms of composite materials were found in 1500 BC by the Egyptians. They made their structures and houses using composite bricks created out of mud and straw as presented to be stronger and to generate compressive forces that allow them to better adhere together increasing the structural integrity of their buildings. In 1200 AD, Mangoes created composite bows made out of wood and animal bone. At the time they were the most powerful weapons on the face of the planet until guns were invented. In 1936, Ray Greene from Toledo, Ohio, created the first composite sailing dinghy made out of a polyester resin. The 16-foot boat started downstream marine boating, and today it is still made with polyester along with fiber glass. In 1958, composite materials were first employed in Chance Vought

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Aircrafts by Brennen Foch. In 1970, were manufactured using 2% of carbon fiber composites?

LITERATURE REVIEW

In 1981, the carbon fiber mono car, also known as the driver compartment, was developed and introduced in the Formula 1 racing car. This was considered as one of the greatest significant contributions to safety in the Formula 1 racing since its beginning in the early 1950s. Fast forwarding, the Boeing 787 Dreamliner is made out of 50% composites compared to the 1970 2% composites aircraft. The Boeing 787 Dreamliner presented in Figures 1 and 2 is the lightest aircraft on earth [4].

Figure 1: Composite bricks made out of straw and mud.

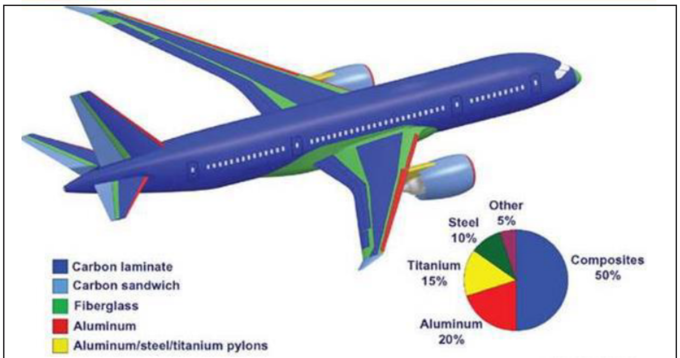

Figure 2: The Boeing 787 dreamliner 50% of composites.

C-C composites

Carbon-carbon composites are those special composites in which both the reinforcing fibers and the matrix material are both pure carbons. Carbon-carbon composites are a new class of engineering materials that are ceramic in nature but exhibit brittle to pseudo plastic behavior. Carbon fiber reinforcements when embedded in carbonaceous matrix material results in C-C composites. They can be considered as composites which are a woven mesh of carbon-fibers. As in all composites, the aim is to combine the advantage of high specific strength and stiffness of carbon fibers with the refractory properties of carbon matrix. When the fibers are laid in near-net shapes with multidirectional reinforcements, the result is an ideal high temperature structure [3].

Carbon-carbon composites is desired over different substances because they hold stability and carry out structurally at maximum temperature due to mild weight, strong stiffness, durability, superior thermal coefficients and excessive speed friction resistances.

Composites material groups

Graphite Fiber Reinforcement Plastic (GFRP) and aramids (Kevlar) are the commonly used of the fibers.

Polymer Matrix Composite (PMC) and Fiber Reinforcement Plastic (FRP) are known as Reinforced Plastics. In all of the groups above the fibers have high specific stiffness (stiffness to weight ratio) and high specific strength (strength to weight ratio), percentage can reach up to 80% of reinforced plastic, the matrix materials always are fluorocarbon, silicon, phenolic, and thermoplastics. Fibers can be arranged inside the composites as form of particles (large particles or dispersion) short, long, continuous, or discontinuous (random or aligned) as it shows in the Figure 3 below.

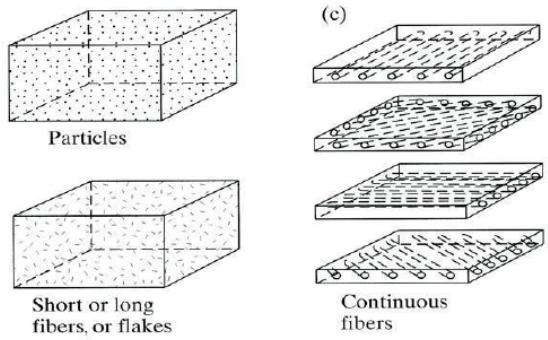

Figure 3: The fiber arranged inside the composite.

Properties of carbon carbon-carbon composites

Excellent Thermal Shock Resistance (Over 2000°C), Low Coefficient of thermal Expansion, High Modulus of Elasticity (GPA), High Thermal conductivity (100 W/m*K) and shock resistance, Low Density (1830 Kg/m^3), High Strength, Low Coefficient of Friction (in Fiber direction), Thermal Resistance in non-oxidizing atmosphere, High Abrasion Resistance high Electrical Conductivity, Non-Brittle Failure, High fracture toughness and do not fracture in a brittle manner like conventional ceramics, Maintain good frictional properties over the entire temperature range with low wear [4].

APPLICATION AREAS AND LIMITATIONS

Although the specific strength and thermal properties of carbon-carbon make it the ideal material for high temperature applications, its use has been restricted by two major factors: the high costs and the susceptibility to oxidation. With more than 60% by volume, aircraft disc brakes are the main application. Compared to a steel brakes carbon-carbon has a 2.5 higher heat capacity, reduces the weight by 40% and doubles the service life. Other main applications are re-entry heat shields for space vehicles and missiles and rocket nozzles (Figures 4-8).

Since the first use of carbon-carbon in aircraft brakes in 1974, major research programs have led to new applications, of which some are

Racing car brakes and clutches

Hot glass transfer elements

Protective shielding

Vacuum/inert gas furnace insulation

Hot pressing molds

Metal sintering trays

Electronic circuit board thermal planes

Semiconductor manufacturing components

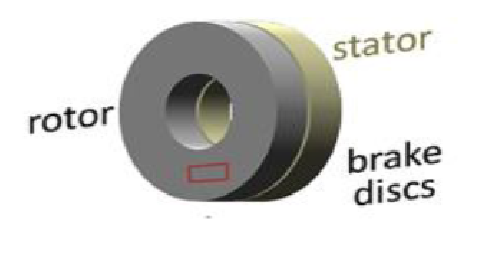

Figure 4: Brake discs made of c-c composite.

High Performance Braking System, Refractory Material, Hot-Pressed dies (brake pads), Turbo-Jet Engine Components, Heating Elements, Missile Nose-Tips, Rocket Motor Throats, Leading Edges (Space Shuttle, Agni missile), Heat Shields, X-Ray Targets, Aircraft Brakes, Reentry vehicles, Biomedical implants, Engine pistons, Electronic heat sinks, Automotive and motorcycle bodies. The brake discs for high-speed aircrafts like Mirage 2000, Concorde, and Airbus-320 are some of the example where the favorable frictional properties were put to use aerospace and defense, mainly for aircraft brake discs, rocket re-entry nose tips, leading edges in high performance aerospace vehicles and parts of rocket nozzles. About 70% of the production of carbon/carbon composites worldwide is used at present for aircraft brake discs [1].

Very few applications of carbon/carbon composites have been realized for general engineering industries. the reasons can be Cost of carbon/carbon composites (compared to conventional materials used at present in different general engineering industries in spite of carbon/carbon composites having far superior specific performance compared to conventional materials) is thought to be the main reason. Carbon/carbon composites are still economically unviable compared to conventional materials used in these general applications. The first-generation CC composites had the limitation of proneness to oxidation over long exposures. However, with the advent of second generation oxidation-resistant composites, this limitation was overcome [5].

FABRICATION PROTECTION AND COST REDUCTION

Fabrication

The processing step is broadly made up of the following steps

Understanding of interaction between carbon fibers and the matrix (established at the polymer stage).

Since the material has to be heat treated to the temperatures of the order of 3000°C, a couple of times during the processing of the product, it is very energy intensive, Some of the other important parameters, which control the properties of carbon/carbon composites, are: Properties of reinforcing carbon fibers

Properties of matrix material

Fiber volume fraction and its distribution

Interface between reinforcing fibers and the matrix.

The fourth parameter is still in the process of being understood. It controls not only the final mechanical and thermal properties of the composites but also the pseudo plasticity of the composites as well. In order to obtain good load transfer between fibers and the matrix, an optimum adhesion at the interface is necessary. Although the surface roughness of the reinforcement contributes to the adhesion, surface bonding is one of the most important factors. It is influenced by the presence of chemically active groups on the surface of the fiber. A compromise between strong and weak bonding at the interface is necessary to optimize the efficiency with which fiber properties are utilized and the fracture toughness of the composites increased [1].

Gas phase impregnation (chemical vapor deposition, cvd)

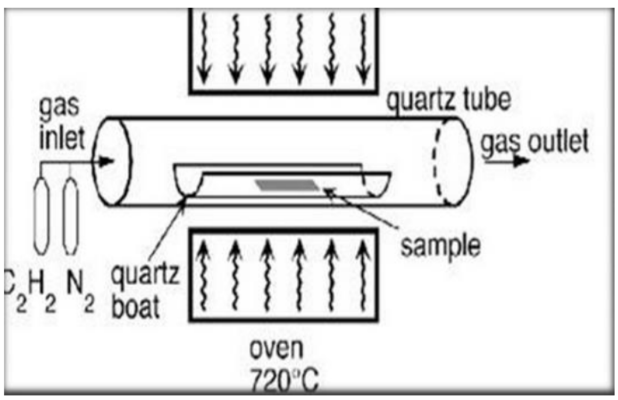

Figure 5: C-v-d process.

This technique uses volatile hydrocarbons such as methane, propane, benzene and other low molecular weight units as precursors [6]. Thermal decomposition is achieved on the heated surface of the carbon fiber substrates resulting in a pyrolytic carbon deposit. This technique can be employed to deposit carbon on to dry fiber preforms or to densify porous CC structures produced by the liquid impregnation route, in which case it is referred to as chemical vapor infiltration. This process route was widely used by the Western countries for the production of thinner parts like aircraft break discs and nozzles. CC process technology using CVD technique is yet to be established [3].

Liquid phase impregnation process

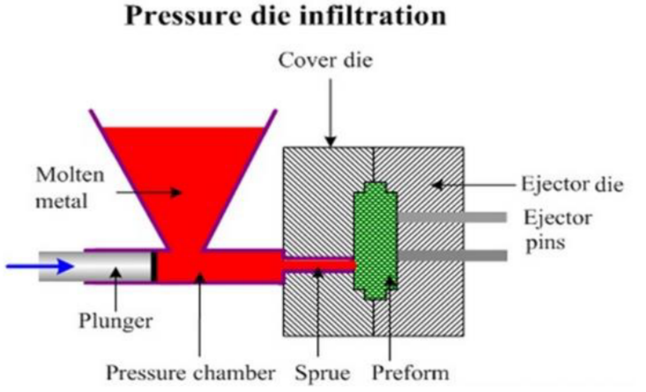

Figure 6: Liquid phase impregnation process.

This process involves impregnation with liquid impregnates like coal tar/petroleum pitches and high char-yielding thermosetting resins. The criterion for selection of impregnates is based on the characteristics like viscosity, carbon yield, matrix microstructure and matrix crystalline structure which are considerably influenced by the time-temperature pressure relationships during the process. The two general categories are aromatic, ring-structured, conventional thermosetting resins such as phenolics, furans and advanced resins like ethynyl, pyrenes or pitches based on coal tar, petroleum and their blends. Figure 4 shows the C-C manufacturing process using the multiple impregnations, carbonization (1000°C), high pressure (1000 bars) carbonization (HIP) and graphitization (2750°C). In atmospheric pressure carbonization, the carbon yields obtained from pitch are only around 50 per cent i.e. approximating those from high yield thermosetting resins. Yields as high as 90 per cent can be obtained by carbonizing the pitch under high pressure of 1000 bars, thus making the process more efficient. Pressure applied during pyrolysis also affects the matrix microstructure. The higher the pressure the more coarse and isotropic will be the microstructure due to the suppression of gas formation and escape. High pressure also helps in lowering the temperature of mesophase formation in pitch, resulting in highly oriented crystalline structure. The HIP process is the only practical route to lower the production cost of CC composites [3].

Pan-process

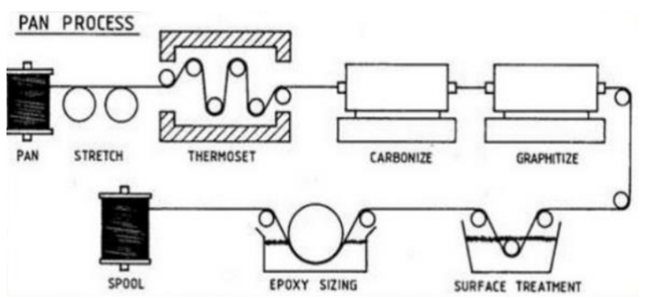

Figure 7: Pan process.

In this method carbon fibers are produced by conversion of polyacrylonitrile(PAN) precursor through the following stages: Stretching filaments from polyacrylonitrile precursor and their thermal oxidation at 200°C. The filaments are held in tension. Carbonization in Nitrogen atmosphere at a temperature about 1200°C for several hours. During this stage non-carbon elements (O, N, H) volatilize resulting in enrichment of the fibers with carbon graphitization at about 2500°C [6].

Oxidation protection of carbon-carbon composites

The main disadvantage of Carbon-Carbon Composites is their low oxidation resistance. Carbon materials react with Oxygen at temperatures above 900°F (482°C). Notwithstanding the attractive mechanical and thermal properties of CC at elevated temperatures, some of the potential applications like turbine structural components which require long term exposure 10 high temperatures are restricted by the inherent reactivity of carbon towards oxygen beyond 500°C. A number of different oxidation protection mechanisms have been explored to improve the oxidation resistance of CC composites. The techniques developed can be categorized as [3]:

A) Surface coatings: single layer/multilayers, using chemical vapor deposition, pack cementation, Physical Vapor Deposition (PVD) and plasma spray.

B) In depth protection includes solgel process, impregnation with inorganic salts (for limited temperature range) and melt impregnation or in-depth deposition of sic matrix.

With the external protection methods, the thermal expansion mismatch between carbon material and possible refractory coatings is the main problem to be overcome. Micro cracks developed in refractory layers have to be sealed with glassy coatings. The best oxidation resistance was achieved in which CVD surface coatings were formed in addition to in depth protection. Internal protection methods include: -

Direct removal and or deactivation of catalytic impurities, and

Incorporation of oxidation inhibitors and total or partial substitution of matrix material. A successful protection system comprises a coating, internal inhibitor and a compatible substrate since carbon-carbon composites.

DISCUSSION

Cost reduction

The cost of carbon/carbon composites depends not only on the cost of raw materials, processing etc. But also, on the end product configuration. In case of carbon/carbon composites, the major cost is contributed by the processing stage. It is 52% of the total cost as compared to only 5% in case of CFRP. One of the major challenges to introduce carbon/carbon composites in general engineering mass applications is to reduce the cost of these materials so as to bring it at par (performance/unit price) with other conventional materials. The major areas where reduction can take place are:

Reduction in the cost of carbon fibers

Reduction in the cost of processing

Technologists seem to have exhausted all the available tools for any further improvement. Altogether new approaches are being tried using "higher throughputs", "New Precursor chemistry", Carbon fiber from Lignin" including Microwave Processing etc. But these are still at exploration stage. Some of the more important cases are reported below:

Plasma enhanced vapor infiltration technique

Gives an overall diagram for processing of carbon composites using this technique. This technique provides a method for controlled densification of a porous article having either open or closed porosity. In this approach, densification is extremely rapid as compared with conventional techniques, and involves only a single processing cycle instead of multiple cycles of carbon deposition and surface machining. The densification time can be reduced to a few percent of that required in conventional processing methods.

A plasma is formed in a reactor by high frequency induction. The article to be densified is immersed into the plasma so that the plasma completely surrounds the article. A source of densifying species is introduced into the plasma. For example, methane gas can be taken. The source gas dissociates and the disassociated carbon thereafter gets ionized. Since the article is immersed into the plasma, it assumes a small negative potential relative to plasma. To increase the negative potential, a further negative bias to the article is given from outside. As a result of this, the total negative bias causes the ionized carbon species to be accelerated towards the article and these species finally deposit into the pores.

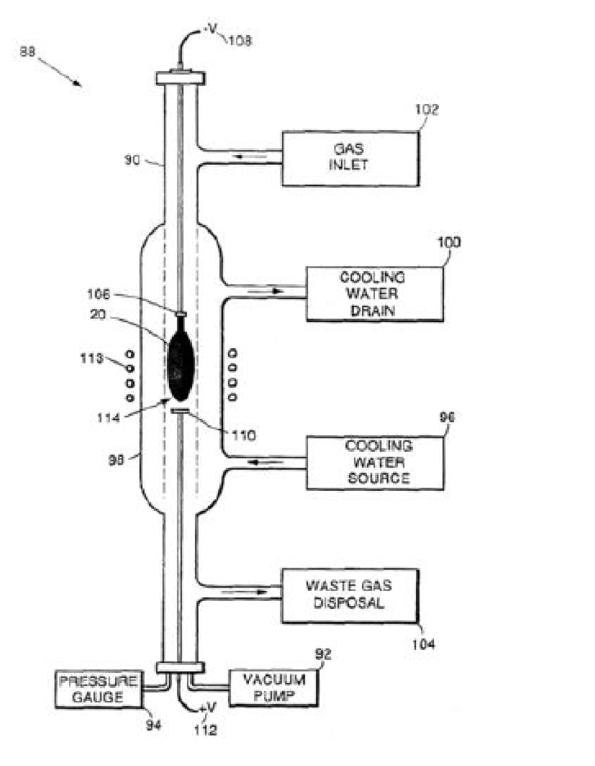

Figure 8: Plasma enhanced vapor infiltration technique.

Depending upon the thickness of the sample the negative bias has to be selected accordingly. As is obvious, the center (pore) of the article gets densified first. Thereafter one will have to reduce the negative bias to densify the article at a lesser depth. Extending this principle, the applied bias voltage has to be gradually reduced to move the zone of densification towards external surface of the article. It is a single step infiltration technique which cuts down both on processing time, required temperatures and avoids any machining as well [7].

Densification of porous structures using super critically fluid technique

In this process, the porous article is immersed in a liquid hydrocarbon and is heated through induction so as to form, through decomposition of the hydrocarbon, carbon or pyrolytic graphite which is deposited in the pores or cavities of the porous article. Figure 9 explains the process of densification and the density of 1.75 g/cc can be achieved in a period of 2 hours compared to 80 hours by conventional method. In this process the article (preform) placed on a rotary support is immersed in a liquid hydrocarbon, such as cyclohexane.

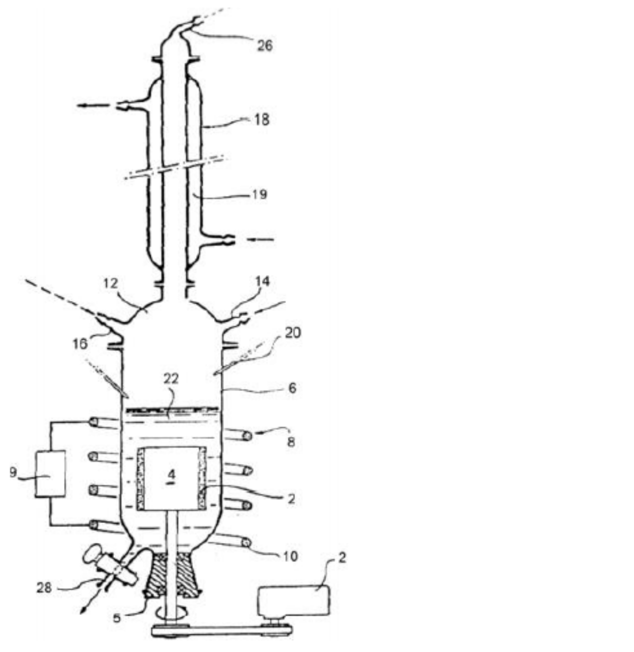

Figure 9: Schematic of densification of C/C composites.

The air present in the system is expelled and the system is heated through induction heater using inert gas. The heated liquid hydrocarbon vaporizes and then decomposes into carbon or pyrolytic graphite and hydrogen.

Single step fabrication of high-density carbon/carbon composites

A special technique of processing high density composites has been developed using a special type of a sample holder for heat treatment of polymer composite material up to 1000°C. In this sample holder, green composites are placed and are covered from both the sides by two other plates. Finally, these three plates were sandwiched; keeping plate containing composite samples in the center. This sample holder was kept for carbonization up to 1000°C in an inert atmosphere keeping the desired heating rates. These were heat treated to 2000°C and 2600°C in inert atmosphere [7, 8].

CONCLUSION

Carbon-carbon composites with their numerous applicational properties are going to pave the way to various engineering applications given the fact that various improvements are undertaken to improve its processing cost and detail analysis of its microstructure is done.

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