Evaluation of C/C-SiC Composites as Potential Candidate Materials for High Performance Braking Systems

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Abstract. This paper is aimed at evaluating the characteristic and performance of C/C-SiC composites as potential candidate materials for high performance braking system. A set of material specifications had been derived from specific engineering design requirements. Analysis was performed by formulating the function(s), constraint(s), and objective(s) of design and materials selection. Function of a friction material is chiefly to provide friction, absorb and dissipate energy. It is done while withstanding load and maintaining the structural adequacy and characteristic of tribology at high temperature. Objective of the material selection and design is to maximize the absorption and dissipation of energy and to minimize weight and cost. Candidate materials were evaluated based on their friction and wear, thermal capacity and conductivity, structural properties, manufacturing properties, and densities. The present paper provides a state of the art example on how materials – function – geometry – design, are all interrelated.

1. Introduction
Braking system is one of the most important parts in mechanical design. Challenging engineering design requirements along with such other critical issues as safety, liability, health, environment, and energy, has driven the development of new friction materials. On the other hand, the discovery of friction materials, which is also pushed by science and technology, has promoted the development friction system design. The development of friction materials is strongly related to the design and applications.

One of the major applications of friction materials is in transportation vehicles. Development of advanced friction materials was essentially ‘pulled’ by the need of aerospace and military industries that are considered as the frontiers in advanced technology. Carbon/Carbon composites, which were attributed to Brennan Forcht of Chance Vought Aircraft, were initially developed in 1958 to respond the need of US space and defense industries[1]. Carbon/Carbon composites, which were particularly developed to meet a set of material specifications dictated by specific design objectives, then had become one of the important friction materials for lightweight and high performance applications.

Use of Carbon/Carbon composite materials in commercial passenger aircraft braking systems dates back to 1973 when the materials, which were provided by Dunlop, went to the first trial on VC10 aircraft before becoming a standard attachment on supersonic passenger aircraft Concorde in 1974[1,2]. The technology, which is formerly directed to advanced applications, has been recently adopted and developed for a wider range of engineering applications. By the end of the 21th century, about 60% volume of Carbon/Carbon composites had been used in Aircraft Braking System in more than 50 types of aircrafts[1]. Recently, the materials have become the prime choice for aircrafts and other high performance braking systems involving military aircrafts, commercial aircrafts, and racing cars[1-4].

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Carbon/Carbon composites are basically a carbonaceous matrix composite reinforced by carbon fiber. Prior to further discussion it is important to specify the carbon materials related to the braking system. According to Blanco[4] carbon materials is best described as the defective form graphite that, along with diamond, are the dominant crystalline form of carbon. Blanco[4] classified carbon materials into several groups based upon its structure. Graphitic carbon materials are carbon materials that have a three dimensional graphite lattice. Non-graphitic carbon materials, which do not have a three dimensional graphite lattice, can be divided into graphitizable and non-graphitizable carbon materials. The graphitizable carbon materials transform into three dimensional graphite lattices when it is heat treated up to 3000°C. Non graphitizable carbon materials are isotropic whereas the graphitizable ones are non-isotropic. Referring to Blanco[4] the key different between the two categories is in the mode of relative arrangement of the constituent graphite layers. In the isotropic, non-graphitizable, carbon materials, the graphene layers are smaller and arranged relative to each other and bonded to each other in all directions. In graphitizable, anisotropic, carbon materials, the graphene layers are larger and arranged parallel to each other and bonded to each other.

Graphitic carbon materials are very attractive for aerospace and other rigorous applications due to such a unique combination of properties that are not demonstrated by other materials. Windhorst[1] revealed such important properties associated with carbon materials as low density, high thermal conductivity and shock resistance, low thermal expansion and high modulus. Blanco[4] specified more detailed characteristics of graphitic carbon materials related to braking systems. Graphitic carbon materials have a high melting temperature, high thermal conductivity, high thermal capacity, and stable coefficient of friction. The materials provide interfacial ‘debris’ that creates frictional surface and serve simultaneously intrinsically as frictional and structural materials. It was also revealed that the materials do not ‘fatigue’ as understood in metal.

Properties of Carbon Materials and hence Carbon/Carbon Composites materials are highly dependent on manufacturing routes, raw materials, processes variables, as well as reinforcements, treatments, and other modifications. Windhorst[1] has revealed some factors that affect the quality of the materials involving the quality of polymer matrix composite from which Carbon/Carbon composites are made, the choice of pitch that affects the carbon yield, the choice of carbon fiber, the microstructure of meso-phase (pitch-based), the wave pattern of carbon fabric, the matrix bond strength, carbonization method/medium, and surface treatment of carbon fibers.

Structural integrity and properties at higher temperature is one of the most important attributes for the designed applications. Windhorst[1] revealed that the materials capable of retaining structural integrity at above 1000°C and withstanding temperature in excess of 2000°C without major deformation. It was also revealed that the mechanical properties are much superior compared to the conventional graphite as it can be tailored in 3-D to withstand damage and exhibit minimum delamination crack growth under interlaminar shearing. Referring to Windhorst[1] heat treatment sequences that involve carbonizing at 1000°C followed by graphitization at 2700°C, result in a 54% increase in flexural strength, 40% decrease in the interlaminar strength, and a 93% increase in the flexural modulus. It was also revealed that the choice of graphitization temperature will affect the toughness of composites. In general, compressive properties of composites are dictated by the carbon matrix whereas the tensile properties are related to the reinforcement. The other important characteristics revealed by Windhorst[1] are the increase of tensile strength at 1200°C and the non-catastrophic, gradual, graceful failure.

Despite of its engineering excellence carbon materials exhibit some important limitations. Of the major drawbacks are that the material suffers oxidation at temperature above 320°C[1] and burning away at 500°C[5]. This situation will have a serious consequence to the fiber matrix interface quality and the strength of bundles[1]. Extensive discussion about the carbon gasification reactions, structure and surface oxygen formation, and properties of surface oxygen complexes was presented by Blanco[4] aimed at giving clear understanding about such conditions affecting brake performance as the presence of air (oxygen), carbondioxide, water vapor, atmospheric and operating temperatures, and intensity of aircraft use.
Insufficient friction stability of Carbon/Carbon composite caused by humidity and temperature along with low wear resistance has also important become issues. Chen[6] studied the effects of humidity on the tribology behavior of Carbon/Carbon composites made from different types of fiber and revealed the close relationship among humidity, surface morphology, and tribology. Gomes[7] studied the effects of temperature on the tribology behavior of Carbon/Carbon composite and denoted the probable change of this behavior at high temperature caused by fiber debonding and fracture. Krenkel[3] revealed that these conditions prevent the practical use carbon materials in passenger cars and trains or emergency breaks of cranes or lifts.

Efforts have been done to improve the properties and applications of Carbon/Carbon composites. In 1980s the development was mainly focused on increasing the specific strength and strain to failure, increasing static friction coefficient, and reducing the manufacturing cost[2].

Oxidation has become critical issues in the development of Carbon/Carbon composites materials as the materials are designed to experience oxidizing atmosphere at elevated temperature either for short term (high temperature) or long term (low temperature). Many efforts have been performed to deal with this critical issue. Bacos[8] provided a comprehensive lecture on the protection of Carbon-based Composites. Referring to Bacos[8], protection mechanisms, which are highly dependent on the range of temperature, can be divided into 2 approaches. At low temperature, microscopic approach is taken by using poisoning agents which adsorb on the active sites responsible for the carbon gasification. At high temperature, macroscopic approach is selected by the use of a barrier that prevents oxygen diffusion. Further challenge came to the second approach as the mismatch between the substrate and the layer that behave differently at high temperature result in cracks. Bacos[8] reviewed further approaches to deal with the oxidation and cracks on coating including intermediate layer, inhibited matrix, and fiber protection. It was identified the need of oxidation protection systems that are moisture insensitive and able to work above 1800°C for long term applications. Bacos[8] revealed the possibility of graded coatings and mixed layers to fulfill the need. Functionally graded coating design is one of the solutions that have been developed until recently to protect the C/C composites from the oxidation[8].

A major breakthrough came to pass in early 1990s when C/C-SiC composites were investigated as potential braking materials[3]. In transportation, the potential applications of these ceramic composites involve automotive, aircrafts, high speed trains, as well as emergency brake for lifts and cranes[10].

This paper is aimed at evaluating the characteristic and performance of C/C-SiC composites as the potential candidates for high performance braking system. This paper deals with the general characteristic and performance of C/C-SiC composites, which are particularly related to the engineering design requirements of high performance braking systems.

2. Design Requirements of A Braking System
In general, braking system in transportation consists of a rotating part (rotor) clamped by static parts (stators). Braking action takes place when the stators, driven by hydraulic pressure, press the rotor. Specifications of advanced braking system vary from applications to applications. Krenkel[3] has revealed the characteristic of different transportation systems dictating the specification of correspondence breaking systems. In general, their characteristics can be compared by Energy per Brake Disk (MJ) as depicted in Figure 1.
Selection and development of materials for a particular engineering application must be started with the understanding of design. Ashby[11] has suggested a selection strategy to match materials and processes attributes with design requirements. The most critical step of material selection and development is to translate design requirements into a set of material specifications. Referring to Ashby[11], design requirements can be systematically formulated by identifying function(s), constraint(s), and objective(s) of design and material selection. The task is effectively done at the component or sub component level where function(s) and constraint(s) can be defined clearly. The results of analysis were summarized in Figure 2.

Figure 1. Brake System Characteristics of Various Transportations represented by Energy per Brake Disk based on data available from Krenkel[3].

Figure 2. Design Analysis of a Brake System for Materials Specifications
Multifaceted design requirements of high performance braking systems can be learned from an aircraft braking system. Stimson[2] provided a useful background about the design of Concorde aircraft braking system involving working principles and loading conditions, which dictates the selection and development of Carbon/Carbon composites. General configuration and basic components of an aircraft braking system, can be learned from the section of Concorde Wheel and Carbon Brake provided by Stimson[2] (Figure 3 and Figure 4).

Figure 3. Concorde Wheel (After Stimson[2])

Figure 4. Concorde Carbon Brake (After Stimson[2])

Function of braking system is basically to stop the moving parts of a mechanical system. The primary function of braking materials is (1) to provide frictional forces as well as (2) to absorb and dissipate energy that is converted from the kinetic energy. This so called friction materials must be able to carry the functions while withstanding design loading and maintaining its structural adequacy and the interface characteristics of interacting surfaces in motion at high temperature. The objective of the material selection is to maximize the absorption and dissipation of energy. The selection is also aimed at minimizing weight and cost.

Constraints of the design vary depending on the operating conditions. As an illustration, for Concorde brake design, the disk temperature can be 500°C in normal landing or up to 1300°C in cancelled take off condition[2]. The absorbed energy per disc also varies, depending on the
characteristic of the transportation system. With respect to the structural adequacy and integrity, mechanical, thermal, and tribology characteristics must be all together analyzed to identify both bulk and surface stresses material must withstand. A simple qualitative analysis of mechanical loading can be performed based on Stimson[2]. Applied and reactive forces that work on rotor and stator are illustrated in Figure 5. The vertical loading as illustrated in Figure 5 produces deflection on the wheel that must be accommodated in the design. However, the thermal movements of the disk are considerably small. One of the most challenging problems in the design of aircraft braking system is to calculate temperature and thermal stress. Analytical solution of the transient heat conduction problem of friction during the braking for the pad sliding over the infinite disc has been obtained by Yevtushenko[12]. Temperature field and thermal stresses for the friction couple metal-ceramic pad and cast-iron disc were studied. Effects of boundary conditions on the pad at upper surface on the distribution of temperature and thermal stresses were investigated. It was revealed that the obtained solution can be used to model the thermal cracking of the frictional element during braking.

Stimson[2] has specified a set of properties for disk materials in an aircraft braking system. They are (1) high thermal capacity, (2) good strength, impact resistance, and strain to failure, (3) adequate and consistent friction characteristics, and (4) high thermal conductivity. Krenkel[3] has also revealed the important characteristics and performance of materials for advanced braking system in automotive breaking system involving: (1) stable dynamic and static coefficients of friction, (2) high wear stability for lifetime brake systems, (3) low weight to reduce the unsprung mass of the transportation system, (4) high degree of freedom in the structural design (e.g. for internal cooling ducts, attachments), and (5) low life cycle costs.

Thermal properties are very critical for high performance braking application. Thermal capacity and thermal conductivity has been identified as the major design criteria for advanced braking systems. Thermal capacity, the quantity of heat necessary to produce a unit change of temperature in a unit mass of a substance, as well as thermal conductivity, the measure of the ability of material to conduct heat are very important. With respect to thermal conductivity, Krenkel[3] revealed that the ability of material to transfer the heat in transverse direction from the outer region to the centre is critical to prevent the friction surface from overheating. Moreover, thermal shock resistance is also important for the braking materials.

Based on the discussion a set of material specifications for braking can be defined as follow: (1) coefficient of friction, (2) wear resistance, (3) thermal capacity, (4) thermal conductivity, (5) thermal

![Figure 5. Concorde Carbon Brake (After Stimson[2])](image-url)
shock resistance, (6) resistance to environment (oxidation and degradation) (7) modulus of elasticity, (8) strength, (9) strain to failure, (10) density, (11) manufacturability, (12) cost.

3. Characteristics and Performance of C/C-SiC Composites

Carbon/Carbon-SiC composites are basically a ceramic composite of SiC matrix with Carbon reinforcements. The properties of these materials vary with the variations of their constituents and processing methods. Carbon fiber decreases the brittleness of SiC matrix and hence improving the damage tolerance of the materials. On the other hand, SiC increases thermal stability and resistance to severe environment compared to pure C/C composites materials. The new combinations, therefore, offer the possibility of improving usual C/C composites.

Several routes can be employed to manufacture these composites materials. One of the long established methods is the infiltration of molten Silica into porous Carbon/Carbon composites. The method is known as Liquid Siliconization Infiltration (LSI) or Liquid Phase Infiltration (LPI)[3,5,10]. Krenkel[10] described the LSI process for Aerospace applications. Firstly, preforms of Bidirectionally CFRP of 40-50 MPa are pyrolized at 900°C to 1650°C under inert N_2 atmosphere. This is aimed at converting the polymer matrix precursor into amorphous carbon. At 500°C fiber/matrix debonding start to occur and with the increase of temperature the matrix will crack to relax the stress caused by shrinkage. A translaminar microcrack pattern of dense C/C segments of about 300-500 individual fibers is formed in the materials that are subsequently infiltrated with molten Silicon at about 1600°C. The dense carbon matrix inside the bundles acts as a shielding from the highly reactive Silicon. SiC is formed around the segments with only a small fraction of fiber is converted or damage.

Another common method is Chemical Vapor Infiltration (CVI). Specific techniques are developed to achieve a particular geometry and properties required by design. A brief review on CVI process was revealed by Liu[5] involving the isothermal and the forced flow thermal gradient process. In CVI, the starting materials are porous fiber preforms. Solid are deposited within the network of pores as the substrate is heated and a heterogeneous chemical reaction between gaseous species takes place. Conventional process is limited by the thickness of materials as the reactants will normally take long time to diffuse.

General comparison of mechanical and thermal properties of experimentally and commercially available brake materials are represented in Table 1 based on data available from Stimson[2] and Krenkel[3]. It should be noted that the properties of composites are highly dependent on the composition of its constituents, their configurations, processing, pre-treatments, and post treatments. Demanding sample preparation and tough testing procedures as well as the lack of generally accepted standards will result in a broad variations of measured values and hence difficulties in the evaluation.

| Properties                  | C/C-SiC | C/C Composites | Steel | Copper |
|-----------------------------|---------|----------------|-------|--------|
| Specific Heat (J/(gK))      | 0.6-2.2 | 1.42           | 0.59  | 0.42   |
| Thermal Conductivity (J/(m.s.K)) | 7-40 | 10-150         | 59    | 346    |
| Coefficient of Linear Expansion (10^6/K) | 0.5-6.5 | 0-8           | 14    | 18     |
| Tensile Strength (MPa)     | 65-370  | 66             | 410   | 240    |
| Impact Resistance (J)      | -       | 0.7            | 110   | 55     |
| Strain to Failure (%)      | 0.25-0.3| 0.55           | 33    | 40     |

*based on Data available from Stimson[2] and Krenkel[3]
3.1. Tribology Properties

Tribology at the interface is very important in determining the performance of friction materials in a high performance braking system. It is generally known that the modification of composite structures will result in the change of the materials tribology at the interface. The phenomena at the interface have been studied extensively but not many results on full-scale test are published openly. Also, the fundamental knowledge about the relationship between materials and their tribology characteristics are not established[11].

Study on the tribology of C/C-SiC composed of the different types of fibers was recently published by Fan and his co-workers[14]. The relationship between structures and tribology properties of aircraft braking materials made from non-woven fiber cloth, short fiber web, and needle fibers are studied from the full scale dynamometer test simulating operating conditions of aircraft braking system. Coefficients of friction at normal landing, overload landing, and rejected take off were reported as 0.27 ± 0.02, 0.26 ± 0.01, and 0.24, respectively. The interactions and mechanism at the interface were studied at micro and sub micro levels. It was revealed that SiC and Si were mostly distributed in the short fiber web layers. Fan[14] also reported that Nano-SiC helps the formation of friction film whereas Micro-SiC enhances the ploughing action of the debris.

Study on wear mechanism of C/C-SiC at a laboratory scale test has also been reported. The most recent works are published by Fan and his co-workers[15]. It was reported that the main wear mechanism were grain-abrasion, oxidation-abrasion, fatigue wear, and adhesive wear, which simultaneously taken place and mutually enhanced the interacting mechanisms. The interaction between C/C-SiC and other braking materials has also been studied. Stadler[16,17] has reported the frictional and wear behavior of sintered metal matrix composites pads and linings in contact with C/C-SiC composites brake discs.

3.2. Thermal Properties

It has been discussion previously that the thermal capacity and conductivity are very important characteristics of C/C-SiC friction materials. It was also revealed that the increase of temperature due to the absorption and dissipation of energy converted from the kinetic energy will influence the temperature distribution and thermal stress at the surface and hence the stability of tribology performance and structural adequacy of friction materials. Moreover, insufficient conductivity together with low thermal expansion coefficient and low stiffness will cause a thermal shock. Therefore, one of the aims of material design is to absorb and dissipate the energy as many as possible away from the matched surface.

Krenkel[3] has revealed the importance of transverse thermal conductivity in the design of materials and geometry for braking system. It was generally assumed that transverse conductivity will reduce the areal braking performance locally resulting in more stable coefficient of friction. One of the advantages of composite material is the ability to tailor the properties in a particular direction. C/C-SiC composites that are generally made from bi-directionally woven fabrics stacked together provide possibilities to be designed for improved thermal conductivity. Krenkel[3] revealed three different possibilities to increase transverse conductivity involving: (1) using fiber with higher thermal conductivity, (2) increasing the angle between fiber and friction surface, and (3) reducing the ceramic content in the C/C-SiC materials.

3.3. Structural Properties

Structural adequacy is very critical in designing materials for braking system and becoming more important as it is the intrinsic properties that cannot be modified locally as what can be done with the surface characteristics. Basically, ceramics is not suitable for structural applications due to its low fracture toughness. Poor tensile behavior, low strain to failure and low tolerance to damage contributes to this behavior. Carbon reinforcement fiber has opened the possibility of using ceramics for structural materials in braking system. It had been discussed that the mechanical properties of
C/C-SiC composites is dependent on the raw materials, manufacturing route, and processing parameters.

Despite the mechanical properties are better than that of monolithic ceramics, Despres[18] revealed the unusual tensile stress and strain behavior of these promising materials as represented in Figure 6. Referring to Despres[18], material exhibits elastic behavior from 0-A that is dependent on the fraction volume of fiber/matrix. At point A, failure occurs in the matrix due to its lower stress bearing capacity compared to the fiber strength. As the failure disseminates, the matrix is extended at high strain value without an increase of stress resulting in a plateau behavior A-B. At B, multiple fractures are maximized and the slope of the curve is mainly dictated by the modulus of fiber assuming that fiber/matrix bond is weak. Then, the slope of the curve increases along B-C.

When the strain to rupture value of the fibers is reached, they start to collapse one after another from C to D. According to Despres[18], the fact that fibers response successively instead of simultaneously are not expected. To improve the quality of the composites, Despres[18] revealed the necessity of adding the third component i.e. the interphase of C/C-SiC composites.

![Figure 6. Sketch of the tensile stress/strain behaviour of a bulk ceramic (curve 1) and a fiber-reinforced ceramic matrix composite (curve 2) (After Despres[18])](image)

Camus[19] has studied the damage mechanisms and associated mechanical behavior of a 2D C/C-SiC composite made from CVI process when it is subjected to tension and compression at room temperature. It was reported that the material exhibits an extended non-linear stress/strain related to a multistep development of damage comprising transverse matrix micro-cracking, bundle/matrix and inter-bundle debonding as well as thermal residual stress release. In compression, after initially non-linear behavior involving thermal micro-cracks, the composite material behaves linearly until failure.

With respect to the damage mechanism, Camus[19] proposed three or four development stages involving: (1) an elastic response coupled with partial re-opening of thermal micro-crack, (2) multiple matrix micro-cracking perpendicular to the applied loading, (3) crack opening and related fiber/matrix and mostly bundle/matrix and inter-bundle debonding with (4) progressive transfer of load to the fibers that the failure accordingly until composite failure.

In general, it is learned from the previous works that the structural performance of the C/C-SiC composite materials are generally sensitive to the nature of fibers and interfaces as well as the type and direction of loadings.
4. Conclusion

Selection of friction materials and their development are dictated by the evolving requirements of braking system design. C/C-SiC composites have been developed to respond the limits of established friction materials. A set of material specifications had been derived from design requirements and employed to evaluate candidates. Analysis was accomplished by formulating the function(s), constraint(s), and objective(s) of design and materials selection. Primary function of a friction material is to provide friction, absorb and dissipate energy, while withstanding design loading and maintaining its structural adequacy and tribology characteristic at high temperature. The objective of the material selection is to maximize the absorption and dissipation of energy. In addition, it is aimed at minimizing weight and cost.

The candidate materials were evaluated based on their friction and wear characteristics, thermal capacity and conductivity, structural properties, manufacturing properties, and densities. Cost along with such other local and global issues as safety, liability, health, environment, and energy should also be considered in the final selection of materials but beyond the scope of this paper. Tribology, thermal, and load bearing performance of materials for a particular braking system can be further enhanced through the improvement of material/composite design and processes as well as final geometry modification.

Development of Carbon/Carbon Composites Materials for High Performance Braking System provided a state of the art example on how materials – function – geometry – design, are all interrelated.

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