A Review on Properties and Applications of Ceramic Matrix Composites

Ameya G Basutkar, Aniket Kolekar

Department of Mechanical Engineering, Padmashree Dr. D.Y. Patil Institute of Engineering, Management and Research, Akurdi, Savitribai Phule Pune University

Abstract — **Carbon–carbon composites rank first among ceramic composite materials with a spectrum of properties and applications in various sectors. These composites are made of fibres in various directions and carbonaceous polymers and hydrocarbons as matrix precursors. Their density and properties depend on the type and volume fraction of reinforcement; matrix precursor used and end heat treatment temperature. Composites made with thermosetting resins as matrix precursors possess low densities (1.55–1.75 g/cm^3) and well-distributed micro porosity whereas those made with pitch as the matrix precursor, after densification exhibit densities of (1.8–2.0 g/cm^3) with some mesopores, and those made by the CVD technique with hydrocarbon gases, possess intermediate densities and matrices with close porosities. The former (resin-based) composites exhibit high flexural strength, low toughness and low thermal conductivity, whereas the latter (pitch- and CVD-based) can be made with very high thermal conductivity (400–700 W/MK) in the fibre direction. Carbon–carbon composites are used in a variety of sectors requiring high mechanical properties at elevated temperatures, good frictional properties for brake pads in high speed vehicles or high thermal conductivity for thermal management applications.**

Keywords— **Carbon fibres; carbon–carbon composites; high temperature materials; mechanical/thermal properties.**

I. INTRODUCTION

Ceramic matrix composites (CMCs) are a subgroup of composite materials as well as a subgroup of technical ceramics. They consist of ceramic fibers embedded in a ceramic matrix, thus forming a ceramic fiber reinforced ceramic (CFRC) material. The matrix and fibers can consist of any ceramic material, whereby carbon and carbon fibers can also be considered a ceramic material. [1]

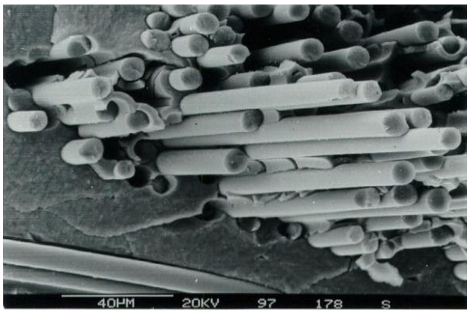

Fig.1 Fracture surface of a fiber-reinforced ceramic composed of SiC fibers and SiC matrix. The fiber pull-out mechanism shown is the key to CMC properties [1]

II. PROPERTIES

A. Mechanical Properties

The high fracture toughness or crack resistance mentioned above is a result of the following mechanism: under load the ceramic matrix cracks, like any ceramic material, at an elongation of about 0.05%. In CMCs the embedded fibers bridge these crack. This mechanism works only when the matrix can slide along the fibers, which means that there must be a weak bond between the fibers and matrix. A strong bond would require a very high elongation capability of the fiber bridging the crack, and would result in a brittle fracture, as with conventional ceramics. The production of CMC material with high crack resistance requires a step to weaken this bond between the fibers and matrix. This is achieved by depositing a thin layer of pyrolytic carbon or boron nitride on the fibers, which weakens the bond at the fiber/matrix interface leading to the fiber pull-out at crack surfaces. In oxide-CMCs, the high porosity of the matrix is sufficient to establish the weak bond. [2]

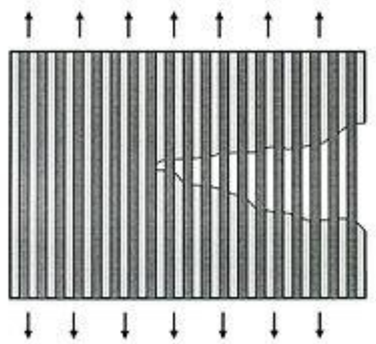

Fig.2 Scheme of crack bridges at the crack tip of ceramic composites [2]

B. Thermal and Electrical Properties

The thermal and electrical properties of the composite are a result of its constituents, namely fibers, matrix and pores as well as their composition. The orientation of the fibers yields anisotropic data. Oxide CMCs are very good electrical insulators, and because of their high porosity their thermal insulation is much better than that of conventional oxide ceramics.

The use of carbon fibers increases the electrical conductivity, provided the fibers contact each other and the voltage source. Silicon carbide matrix is a good thermal conductor. Electrically, it is a semiconductor, and its resistance therefore decreases with increasing temperature. Compared to polycrystalline SiC, the amorphous SiC fibers are relatively poor conductors of heat and electricity. [2]

TABLE I: Thermal and Electrical Properties [2]

Material	CVI-C/SiC	LPI-C/SiC	LSI-C/SiC	CVI-SiC/SiC	SiSiC
Thermal Conductivity (p)[W/mK]	15	11	21	18	>100
Thermal Conductivity (v)[W/mK]	7	5	15	10	>100
Linear Expansion (p)[10^{-6}.1/K]	1.3	1.2	0	2.3	4
Linear Expansion (v)[10^{-6}.1/K]	3	4	3	4	3
Electrical Resistivity (p)[Ω.cm]	-	-	-	-	50

Comments for the table: (p) and (v) refer to data parallel and vertical to fiber orientation of the 2D-fiber structure, respectively. LSI material has the highest thermal conductivity because of its low porosity – an advantage when using it for brake discs. These data are subject to scatter depending on details of the manufacturing processes.
Conventional ceramics are very sensitive to thermal stress because of their high Young's modulus and low elongation capability. Temperature differences and low thermal conductivity create locally different elongations, which together with the high Young's modulus generate high stress. This results in cracks, rupture and brittle failure. In CMCs, the fibers bridge the cracks, and the components show no macroscopic damage, even if the matrix has cracked locally. The application of CMCs in brake disks demonstrates the effectiveness of ceramic composite materials under extreme thermal shock conditions. [2]

III. APPLICATIONS

a. developments for applications in space

During the re-entry phase of space vehicles, the heat shield system is exposed to temperatures above 1500 °C for a few minutes. Only ceramic materials are able to survive such conditions without significant damage and among ceramics only CMCs can adequately handle thermal shocks. The development of CMC-based heat shield systems promises the following advantages:

- Reduced weight
- Higher load carrying capacity of the system
- Reusability for several re-entries
- Better steering during the re-entry phase with CMC flap systems

Fig.3 NASA-space vehicle X-38 during a test flight [3]

In these applications the high temperatures preclude the use of oxide fiber CMCs, because under the expected loads the creep would be too high. Amorphous silicon carbide fibers lose their strength due to re-crystallization at temperatures above 1250 °C. Therefore carbon fibers in a silicon carbide matrix (C/SiC) are used in development programs for these applications. The European program HERMES of ESA, started in the 1980s and for financial reasons abandoned in 1992, has produced first results. Several follow-up programs focused on the development, manufacture, and qualification of nose cap, leading edges and steering flaps for the NASA space vehicle X-38. [3]

B. Application in brake disk

Carbon/carbon (C/C) materials have found their way into the disk brakes of racing cars and airplanes, and C/SiC brake disks manufactured by the LSI process were qualified and are commercially available for luxury vehicles. The advantages of these C/SiC disks are:

- Very little wear, resulting in lifetime use for a car with a normal driving load of 300,000 km, is forecast by manufacturers.
- No fading is experienced, even under high load.
- No surface humidity effect on the friction coefficient shows up, as in C/C brake disks.
- The corrosion resistance, for example to the road salt, is much better than for metal disks.
- The disk mass is only 40% of a metal disk. This translates into less unsprung and rotating mass.

The weight reduction improves shock absorber response, road-holding comfort, agility, fuel economy, and thus driving comfort.
The SiC-matrix of LSI has a very low porosity, which protects the carbon fibers quite well. Brake disks do not experience temperatures above 500 °C for more than a few hours in their lifetime. Oxidation is therefore not a problem in this application. The reduction of manufacturing costs will decide the success of this application for middle-class cars. [4]

Fig.4 LeMans prototype DMC disc Φ380x18 mm [4]

Fig.5 Ferrari F430 front brake disc [4]

IV. CONCLUSION

Significant progress continues to be made in developing ceramic matrix composite components for aircraft engine applications in order to meet the ERA performance goals for reductions in emissions and fuel burn.

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