Chapter 1

Introduction

1.1. Introduction

Due to continuous technical advancements globally, the demand of new materials is increasing day by day. Monolithic materials are not able to meet all the service requirements and serve the required purposes. To fulfil the several applications criteria, composite materials were developed. A composite material is generally composed of a discrete phase (i.e. reinforcement) which is distributed in a continuous phase (i.e. matrix). Composites derive their properties from the characteristics and geometry of its constituents, and their architecture. The nature of interface between different constituents also plays an important role in depicting the properties of composites. Unlike metallic alloys, the constituents of a composite materials retain their physical, chemical and mechanical properties [1]. Composite materials usually exhibit better properties as compared to their constituents when they are used alone.

The reinforcement phase in a composite material is usually in the form of particulate, fibre or both. Particulates have approximately same dimensions in at least two directions whereas fibre has its length much larger than its diameter. The properties of continuous fibre composites can be tailored to a high degree of assurance because the orientation of fibres can be varied preferably. The classification of composite materials is usually based on the physical and the chemical nature of the matrix, e.g. Polymer matrix, Metal matrix and ceramic matrix composites. Intermetallic matrix composites are also emerging at an appreciable rate.

The properties of matrix, reinforcement and the bonding between them, and the surrounding environment affect the mechanical and tribological response of composite materials. Metal Matrix Composites (MMCs) are suitable for applications which require combined properties like strength, thermal conductivity, and damping properties. Due to these properties, MMCs are being used in automotive structures and tribological applications. MMCs are being used for pistons, brake drums and cylinder blocks of automobiles because of better corrosion and wear resistance. The commonly used metal matrices include Al, Mg, Ti, Cu and their alloys. However, the mechanical and tribological properties of MMCs degrade at elevated temperature which limits their usage in high temperature applications.

Polymer matrix composites (PMCs) were developed for superior specific strength. Later their usage in tribological applications was explored and it was found that the polymer matrix composites can be designed to exhibit superior tribological properties. But due to low thermal conductivity of PMCs, there is a localized temperature zone which affects their tribological behaviour. The friction coefficient of PMCs is generally unstable at high temperature. The orientation of fibres in PMCs affects their tribological behaviour. Polymer composites having parallel orientation of fibres are usually preferred over anti-parallel and normal orientation. Polymer composites with the normal orientation of fibres usually exhibit a low wear rate but the risk of sudden seizure is high in normal orientation due to the exposed normal fibres which tend to gouge into the counterface and hence initiate the severe wear or seizure. However, like metals, the properties of PMCs also degrades at high temperature.

The use of ceramics is not new for high temperature applications. According to American Ceramic Society, ceramics are defined as inorganic, non-metallic materials which are usually crystalline in nature and are the compounds formed between metallic and non-metallic elements such as silicon and nitrogen, calcium and oxygen, and aluminium and oxygen [2]. Structural Ceramics and Functional Ceramics are the two broad classifications of ceramics [3]. Structural ceramics are usually based on the mechanical strength, hardness, and toughness, and the functional ceramics are based on electric, magnetic, dielectric, optical, and other properties. Due to low fracture toughness, monolithic ceramics tend to form cracks easily under mechanical and thermomechanical loads, and cracks propagate without any significant resistance to its propagation. To overcome this problem, ceramic matrix composites were developed which exhibit quasi-ductile fracture behavior while maintaining all other advantages of monolithic ceramics [4, 5]. Further, tribological performance of ceramics and its composites is also related to the fracture toughness. Experiments performed by Ishigaki et. al. [6] revealed that friction coefficient of ceramic based materials is inversely related to fracture toughness. Friction coefficient increases with decrease in fracture toughness because occurrence of fracture lead to more consumption of energy which increases friction coefficient. The role of sliding velocity and normal load may be interpreted in terms of extent of fracture in the contact zone, extent of surface film formation and rise in temperature in the contact zone.

Ceramic matrix composites reinforced with ceramic fibres can be used for extreme environmental conditions due to their whole ceramic content. Ceramic fibres generally maintain the attractive properties of monolithic ceramics such as high modulus, high temperature sustainability, and high corrosion resistance [7]. Ceramic fibres are broadly classified into two categories i.e. Oxide and Non-oxide fibres. Oxide fibres are mostly based on alumina (Al_2O_3) and Silica (SiO_2) fibres, and are most suitable for oxidizing environments and high temperatures generally above 1400 ^oC. Non-oxide fibers like Silicon carbide (SiC), Si-C-(N)-O and carbon fibres exhibit higher values of elastic modulus and tensile strength as compared to oxide fibres but they usually possess low oxidation resistance at high temperature. In the group of non-oxide fibres, carbon fibres are mostly used for a wide range of applications. Carbon fibres are few microns thick, strong, light weight and stiff synthetic fibres with long aromatic molecular chains comprised mainly of carbon. These fibres are capable of withstanding extreme conditions of temperature and pressure without losing their structure and properties, and thus can be used with all types of matrices, i.e. polymers, ceramics and metals [8].

In the wide plethora of ceramic fibres reinforced ceramic matrix composites, carbon fibres reinforced carbon matrix (C/C) composites have emerged as promising candidates for high performance and weight sensitive applications. C/C composites exhibit superior thermal and mechanical properties such as high specific heat, high stiffness and toughness, low density, high specific strength, excellent tribological properties, and low coefficient of thermal expansion [9, 10]. First non-oxide CMCs, based on carbon/carbon composites, were developed in the 1970s as lightweight structures for aerospace applications. They were designed as limited life structures as the environmental conditions were highly aggressive and the long term behaviour of these composites was still unknown. Typical representatives for such components were rocket nozzles, engine flaps, leading edges of spacecraft and brake disks of aircraft. Their lifetime comprises several minutes to some few hours under highest thermomechanical requirements which cannot be fulfilled by any other structural material. In contrast to metals and monolithic ceramics which show decrease in strength, C/C composites show increase in strength with increase in temperature. The variation of strength with increase in temperature is shown in Fig. 1.1 for some commonly used composites.

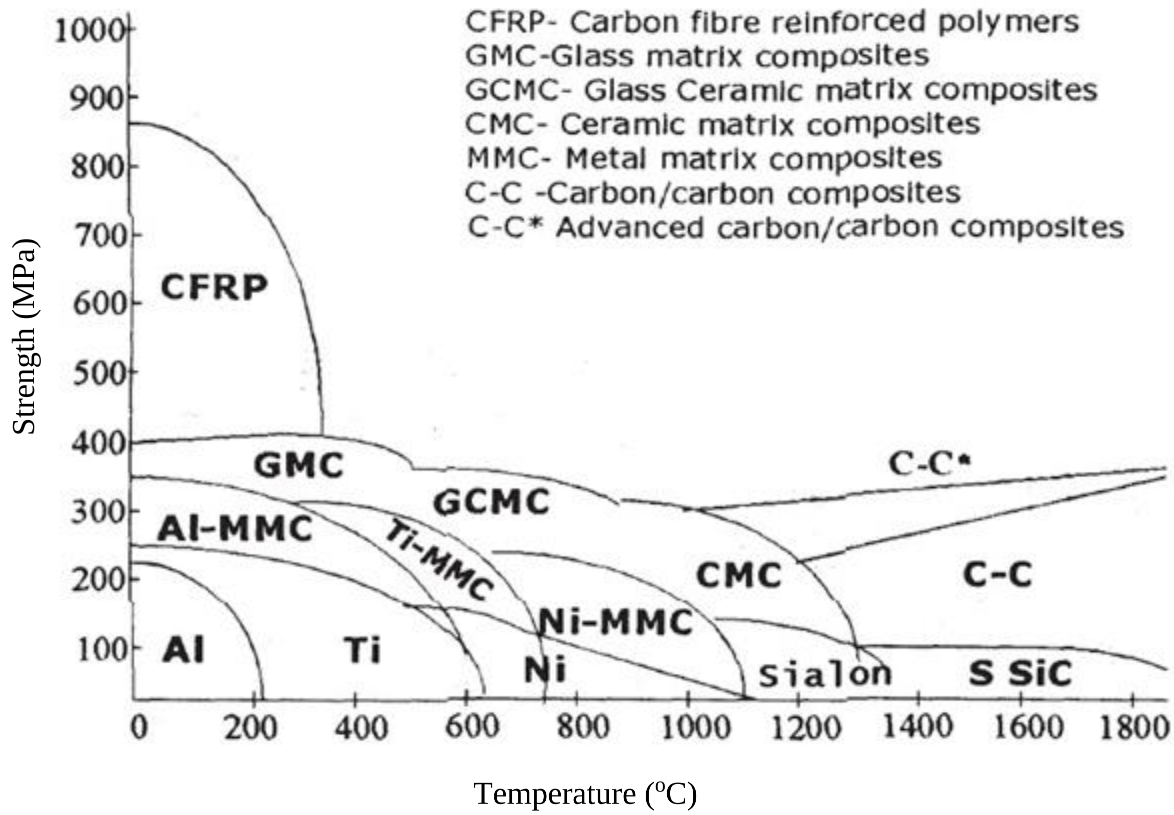

Fig. 1.1. Variation of strength with temperature for some engineering composites. [8]

C/C composites can be fabricated using different techniques such as solid pyrolysis of thermosetting resins, CVD route and pitch route using liquid infiltration and carbonization.

C/C composites are very much sensitive to humidity and show unstable friction behaviour in humid environment [11]. Their oxidation resistance is also low [12, 13]. Thus the high cost, low oxidation resistance and unstable friction behaviour of C/C composites limits its applications [13]. To overcome these disadvantages of C/C composites, SiC was incorporated in the carbon matrix to enhance its oxidation resistance and tribological performance. Incorporation of SiC increases the hardness and thermal stability, and decreases the chemical reactivity which leads to the improvement of frictional properties of

C/C composites. The carbon fibres reinforced carbon and silicon carbide dual matrix (C/C-SiC) composites have high and stable friction coefficient, low wear rate, long service life, and low sensitivity to surroundings and oxidation as compared to C/C composites [12, 14, 15]. The mechanical properties of C/C-SiC composites do not get affected at high temperature [8]. When the weight content of silicon carbide is higher than 20% in the C/C – SiC composites, the composites show lower sensibility to surroundings and temperature [16]. C/C-SiC composites have more density as compared to C/C composites [12]. This makes C/C composites favourable over C/C–SiC composites in weight sensitive applications.

C/C – SiC composites can be fabricated by three different methods i.e. (i) Chemical vapour infiltration (CVI), (ii) Polymer infiltration and pyrolysis (PIP) and (iii) Liquid silicon infiltration (LSI) in which LSI method is widely used for the fabrication of C/C – SiC composites due to higher mechanical and thermal properties obtained after LSI fabrication technique. LSI is also less time consuming and cost efficient process as compared to CVI and PIP process. These three processes have been discussed in the next chapter.

C/C and C/C-SiC are mostly used for the friction elements of brake disks of high speed cars and aircrafts. Friction brakes decelerate a vehicle by transforming the kinetic energy of the vehicle into heat and dissipate that heat into surroundings. The brakes which are used in automotive braking system are generally made of steel or grey cast iron and coupled with polymer composite pads [17]. These materials are used in braking system with moderate loads and limited capability to withstand temperature. These materials have relatively high and stable coefficient of friction, low wear rate and are quiet during operation. [18] However, heavy vehicles require more power for braking than conventional braking system.

The main requirements of high performance brake materials are

- Stable co-efficient of friction (dynamic and static).
- Low wear rate for increased life.
- Low life cycle costs.
- Low weight.
- High degree of freedom in the structural design (for internal cooling ducts, attachments).

Therefore in recent years, C/C and C/C – SiC composites came into picture as high performance brake materials following metal based materials [19, 20]. These composites can provide more friction and can operate at high temperature. For example, many accidents are caused by trucks when their brakes get over-heated while descending a hill and are unable to stop. A 20 ton truck stops at a distance of nearly 80 m by using cast iron brakes after a descend of 5 km at 10 percent incline with 60 km/h velocity. [21] This stopping distance can be reduced to 25 m by using carbon-carbon brakes.

1.2. Aim and objective of work

Most of the literature available for C/C and C/C-SiC composites is based on the deformation behaviour, and friction and wear characteristics for fully conformal surfaces. A very little literature is available on tribological behaviour under low conformity and non-conformal hertzian contacts. Material behaviour depends on the stress configuration. In case of low conformity and non-conformal hertzian contacts, localized contact conditions yield very high stress regions. In high stress regions, material wear out very rapidly due to localized rise in temperature and behaviour is different as compared to bulk material.

The friction coefficient of C/C and C/C – SiC composites also varies significantly with braking conditions. Most of the literature is available on high energy braking conditions. Low energy braking conditions have not been investigated to a significant extent. Further, friction and wear behaviour of C/C and C/C - SiC composites in reciprocating sliding condition has not been investigated. Wear and friction behaviour of material which slides in one direction is different from that which slides in reciprocating manner because of sliding in confined region and less extent of lip formation.

In the light of above, the objective of the present study is to investigate the influence of environment on the sliding behaviour of C/C and C/C-SiC composites with the variation of laminate orientation, surface conformity, braking energy and the sense of sliding. The various environmental conditions and testing methods are presented in Fig. 1.2.

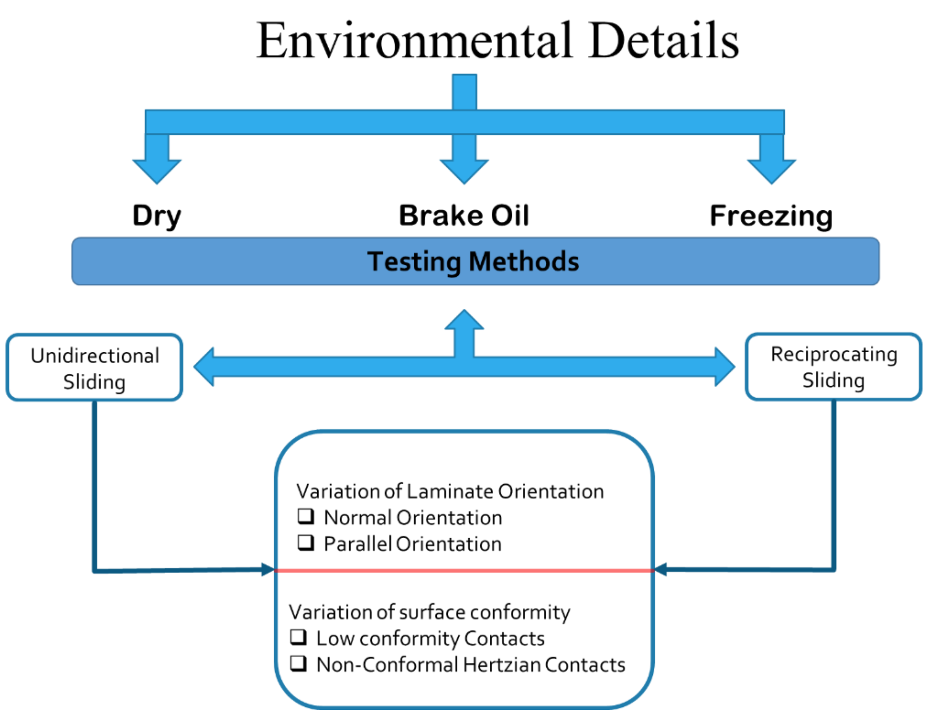

Fig. 1.2. Various environmental details and testing methods used for the present investigation.

The detailed literature review pertaining to the development of C/C and C/C-SiC composites for various tribological elements and their tribological behaviour under several braking energy conditions and different environments is presented in the next chapter.

1.3. Organization of thesis

This thesis has been divided into ten chapters. **The first chapter** was intended to introduce the Carbon-Carbon and Carbon-Carbon-Silicon Carbide composites and then present the aim and objective of work.

Chapter 2; Represents the critical literature review on the tribological behaviour of C/C and C/C-SiC composites and the factors affecting their tribological behaviour.

Chapter 3; Represents the tribological behaviour of C/C and C/C-SiC composites in dry environment with variation of laminate orientation and surface conformity.

Chapter 4: Describes the effect of brake oil on the tribological behaviour of C/C and C/C-SiC composites.

Chapter 5: Represents the effect of freezing conditions on the tribological behaviour of C/C and C/C-SiC composites.

Chapter 6; Describes the reciprocating sliding tribology of C/C and C/C-SiC composites in self and complementary mated pairs.

Chapter 7; Represents the comparative study of tribological behaviour in all the three environments.

Chapter 8; Represents the concluding remarks, and a developed mathematical model for friction coefficient and future scope will be discussed in **Chapter 9** and **10** respectively.