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Effect of Type of Carbon Matrix on Tribological Properties of C/C Aircraft Brake Discs

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ABSTRACT

Four type of Carbon/Carbon (C/C) composite brake discs (A, B, C, D) were manufactured using different process routes, using spun yarn graphitised carbon fabric as reinforcement. These discs were densified with different types of carbon matrices derived from different precursor materials. C/C brake disc of type A is having carbon matrix derived from pitch precursor, type B has a mixture of resin and pitch derived carbon matrices, type C has a combination of resin derived, pyro and pitch derived carbons and type D has pyro and pitch derived carbon matrices. Friction and wear performance of these brake discs were studied by simulating aircraft landing braking energies (normal and over load) corresponding to one interface using disc-on-disc dynamometer. It was found that the type of carbon matrix influences the nature of friction film formed, which in turn affects the wear rate of C/C brake discs. It was also discussed how the matrix characteristics affected the mechanical properties and the friction film formed affect the coefficient of friction of each type of disc.

Keywords: Carbon-carbon composites; Aircraft brakes; Carbon matrix; Friction; Wear; Phenomenon

1. INTRODUCTION

One of the major applications of carbon-carbon (C/C) composites is the aircraft brakes[1,2]. C/C brake discs are being used in several civilian and military aircraft, because of the severe thermo-mechanical loading of the heat pack. C/C composites are ideal for aircraft brake application, as they possess excellent properties like high specific heat, high thermal conductivity, low coefficient of thermal expansion, retention of mechanical strength at elevated temperatures, and excellent tribological characteristics[3]. In spite of their high cost, attributes like light weight, low wear, high and stable coefficient of friction (COF) over a wide temperature range, make them ideal candidate for aircraft brake application[4].

The tribological characteristics of C/C brakes depend mainly on the composition of the brake material, the process and usage conditions. The COF of brakes is a critical parameter. The COF should be high enough to generate the required torque on application of brake pressure, to achieve the required stop time. At the same time, it should not be too high so that brakes become grabby or over sensitive to pressure, or too low to become sluggish. High values of COF and higher values of peak to average ratio of friction coefficient are not desirable in the functioning of brake management system.

Wear of C/C brakes directly affects the life of the discs. Lower wear rates are desirable not only to enhance the life but also to avoid the time lapses during frequent changeover of the heat pack. Several workers have studied the effect of different parameters like energy to be absorbed, brake application speed, brake pressure, process methods, microstructure of wear debris etc., on the wear phenomenon in C/C brake discs[5-10]. The general observation is that, the wear of the C/C brake discs depends on the type of wear debris generated and its subsequent conversion into friction film, which lubricates the friction surfaces. The compactness of the friction film determines the overall wear that takes place in a brake material.

Friction and wear characteristics of C/C brakes depend on several parameters like type of carbon fibre reinforcement, type of matrix, the process parameters, the usage conditions[2] (severity of loading in brakes etc.) and the surrounding environment. Several studies have been carried out and reported in the literature to study the effect of different parameters like properties of fibre reinforcement[11], fibre architecture[12], fibre orientation[13], pressure during densification[9], heat treatment temperature[14], sliding velocity/braking speed and brake pressure[15-16], energy absorbed by the brakes[7], air/nitrogen atmosphere[17] and humidity[18], on friction and wear of C/C aircraft brake discs. The type of carbon matrix is one of the important parameters that influences the friction and wear of C/C brakes. There are three major process routes to fabricate C/C composites viz., liquid pitch impregnation route, resin route and gaseous route i.e. the chemical vapour infiltration (CVI). Many times a combination of these process routes is followed in the fabrication of C/C brake discs, either to get specific properties and/or to optimise the manufacturing costs. Each process has its own advantages and disadvantages. The carbon matrices derived from each one of these processes have unique characteristics.

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Xiong[19], *et al.* have studied the effect of different types of pyro carbon textures on friction and wear of C/C brake discs. They have related the extent of graphitisation of carbon matrix of different microstructures to the tribological characteristics of C/C brakes. Soydan and Philip[20] have also related the microstructure and mechanical properties of C/C brake discs with different types of reinforcements and matrices. These studies mainly focus on the matrices having different pyrolytic carbon textures on friction and wear of C/C brake discs. Hokao[21], *et al.* have studied the friction and wear behaviour of glassy carbon and graphitic carbon in different proportions in the form of particulate composites. It mentions that the composite of glassy carbon with graphite particles shows lower COF compared to either of the pure components. Ming[22], *et al.* have studied the effect of pitch derived and resin derived carbons as secondary matrices in the C/C composite brake discs, where the pyro carbon present as primary matrix. Here the comparison is basically between resin derived and pitch derived carbons. These studies conclude that the presence of resin derived carbon has contributed to lower wear and higher friction coefficient; whereas pitch derived carbon enhances the wear and reduces the friction coefficient. Some contrasting results are obtained in the present study. All these studies reported in the literature were carried out on either pin on disc or ring on ring configurations. In some cases, the test conditions do not represent the actual usage conditions.

Scope of the present work is to study the influence of pitch derived, resin derived and pyro carbons on tribological characteristics of C/C aircraft brakes. Keeping the carbon reinforcement the same, different types of carbon matrices were formed by using different precursors or combination of them. The effect of all the three types of carbon matrices on friction and wear of C/C discs was compared. Efforts were also made to relate the triobological performance of different types of discs, with varying hardness/modulus values and the nature of the friction film formed during braking. The testing was carried out on actual size products on disc-on-disc dynamometer, simulating the aircraft normal landing (NL) energy and over load (OL) energy conditions for one interface.

2. EXPERIMENTAL

2.1 Types of C/C Brake Discs

Four types of C/C brake discs were fabricated at High Temperature Composite Centre of Advanced Systems Laboratory through different process routes using spun yarn graphitised (SYG) carbon fabric as reinforcement. The details of the different types of discs are as given in Table 1.

2.2 Testing

Physical, Mechanical and Tribological properties were evaluated as per relevant ASTM and MIL standards. Optical microscopy and Micro-Raman spectroscopy were used for micro structural studies of these brake disc samples.

2.2.1 Bulk Density

Bulk density of the brake discs was measured from weight and volume of the product.

2.2.2 Optical Microscopy

The optical microscopic images were taken on OLYMPUS make DSX510 digital optical microscope.

2.2.3 Raman Spectroscopy

Raman spectra were recorded on JY T-64000 spectrometer. Microscope was used to focus the laser beam (514.5 nm exciting line of Ar+ laser) on the sample and to collect the Raman signal in the back scattered direction. The area of focus is about 2 μm and the laser power of 25 mW was used.

2.2.4 Hardness

Brinell Hardness of C/C composite samples was measured on QNESS make Q250M Hardness tester using 2.5 mm ball indenter and 62.5 kgf load. The hardness was measured at minimum of five locations and the average is reported.

2.2.5 Compression Modulus

Compression modulus test of C/C composite samples cut from the brake disc was carried out as per ASTM C 695 using a universal testing machine. The sample dimensions were 13x13x13 mm^3. The cross head speed used was 0.5 mm/min. The modulus was calculated from the slope of the initial straight line portion of the stress vs strain plot.

2.2.6 Dynamometer Testing

The COF and wear rate of C/C brake discs were evaluated using disc-on-disc (DOD) brake dynamometer with variable inertia. The dynamometer test procedure was derived from the MIL standard, MIL-W-5013L. The testing was carried out using a pair of discs consisting of a rotor and a stator simulating aircraft normal and overload brake energy conditions corresponding to one interface. The test schedule calls for five blocks of testing where each block consists of 9 NL energy runs and 1 OL energy run. Thus total of 50 braking stops (45 NL energy + 5 OL energy) were conducted on each type of disc. A C/C rotor mounted on a rotating axle on which, the inertia wheels were engaged, was rotated to the required

Table 1. Details of different types of C/C brake discs

Brake disc sample	Reinforcement	Carbon matrix precursor		Bulk density (g/cc)
		Primary	Secondary	
Type A	SYG	Coal tar pitch	Coal tar pitch	1.86
Type B	SYG	Phenolic Resin	Coal tar pitch	1.80
Type C	SYG	Phenolic resin	1. Methane 2. Coal tar pitch	1.74
Type D	SYG	Methane	Coal tar pitch	1.77

rpm corresponding to the aircraft's linear velocity of 80 m/s in case of NL energy, 84 m/sec in case of OL energy conditions. After attaining the required rpm, the motor was switched off and then the rotor was brought to complete stop by applying brake pressure through stator mounted on the opposite axle. The brake pressure was chosen to achieve the stop time of 27 s, simulating 3 m/s^2 deceleration. The brake torque vs time was recorded and the average torque and COF for each run was calculated. The wear rate was measured in terms of the thickness loss per face of the brake disc per stop. It was measured after each block of testing and the average value of 5 block is reported.

3. RESULTS AND DISCUSSION

3.1 Microstructure

The optical microscopic images of the four type of discs are as shown in Fig. 1. From this figure it may be observed how the different types of carbon matrices are distributed within the composite. In type A discs, the matrix is exclusively made up of pitch derived carbon. In type B discs, the pitch derived carbon is found around the carbon fibre and also in the bulk. Large chunks of resin derived carbon are found. In type C discs the pyro carbon is found to form a layer around the fibre and also it is deposited in the cracks within the matrix. In type D discs, the pyro carbon is observed to have formed interface around each carbon fibre and pitch derived carbon is seen in the rest of the matrix portion.

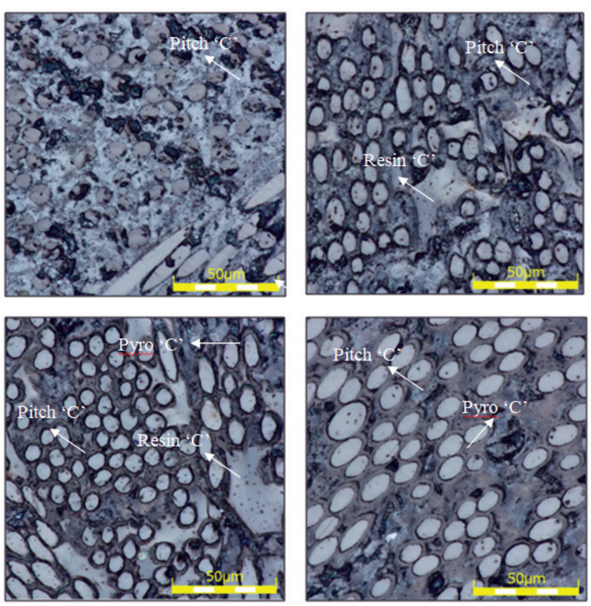

Figure 1. Optical microscopic images of C/C brake disc samples of type A, B, C and D.

3.2 Wear Rate

The wear rate of C/C brake discs of type A, B, C, and D are as shown in Fig. 2.

From the Fig. 2 it may be observed that, the wear rate of type D discs is the lowest and that of type B is the highest. Type A and type C discs showed more or less the same wear rates falling in between these two extremes. In general, harder the material, lower the wear. This is only a general observation,

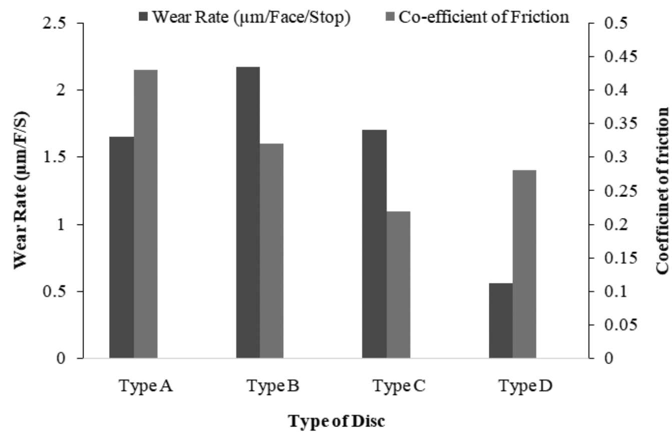

Figure 2. Co-efficient of friction and wear rate of C/C brake discs of types A, B, C and D.

because the tribo-films or the friction films formed during the rubbing also play a major role in controlling the wear process[23]. The wear phenomenon in C/C brake discs depends on the nature of the friction film formed at rubbing interface. The formation of friction film strongly depends on the type of wear debris formed and subsequently the way the wear debris gets converted into friction film. This friction film is important in lubricating the friction surfaces and protecting them from further wear. Cohesive friction film, adhering strongly to the base material is important, for effective lubrication of friction surfaces and achieving lower wear rate. The friction surfaces of all the four type of discs are as shown in the Fig. 3.

Type D discs have developed a thin, compact friction film shown in the Figs. 3(f)-3(g), adhering strongly to the friction surface. The wear debris formed in this type of discs could be easily converted into friction film. This was because, the wear debris coming from the matrix was a combination of pyro 'C' and pitch derived 'C', where both were more graphitic compared to resin 'C' (shown in the Fig. 4) and hence could be sheared easily and sintered strongly. As the wear debris was converted into the friction film quickly, further wear did not take place. The integrity of the friction film observed in this case was due to the thin friction film formation by strong adhesion of wear particle with one another and with substrate.

In case of type B discs, the friction film was not cohesive. From the Figs. 3(c)-3(d), it may be observed that, some portion

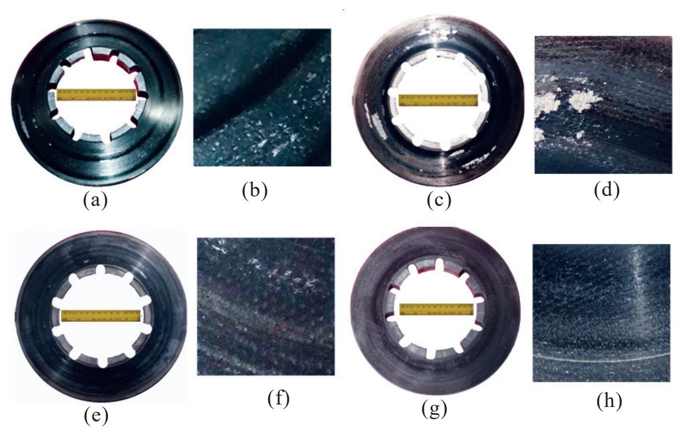

Figure 3. Photographs of friction surfaces of Type A, Type B, Type C and Type D discs.

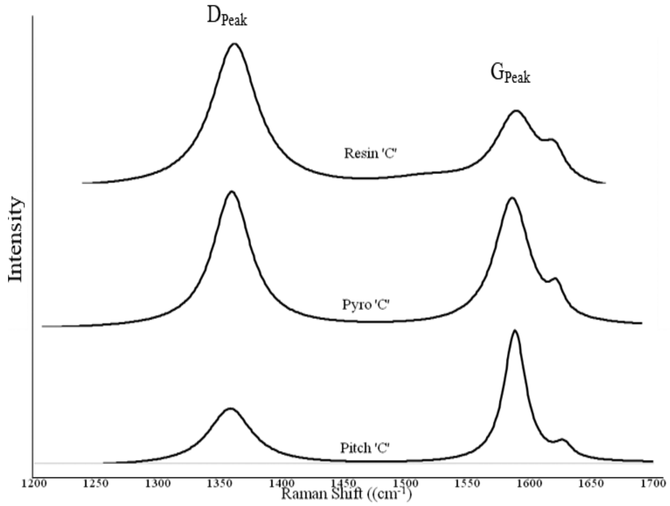

Figure 4. Raman spectra of different types of carbon matrices.

of the friction film is broken and the subsurface is exposed at different locations on the rubbing surface. In this case, the wear debris contained resin derived carbon, which is non graphitic in nature, and cannot be sheared easily, leading to the delay in friction film formation. Hence more wear took place, and led to thicker friction film formation, which was less compact and easily breakable and hence not effective in protecting the subsurface by providing continuous lubrication. Type A and type C discs have shown similar wear rates in spite of having different compositions and big variation in mechanical properties (Figs. 5 and 6). The matrix carbon in type A discs was derived from pitch, which is more graphitic and helps in the formation of lubricating friction film. Whereas the matrix of type C discs was a combination of resin derived, pyro and pitch derived carbons. The effect of amorphous resin derived carbon was moderated by more graphitic pyro and pitch derived carbons and helped in the formation of good friction film.

Carbon matrix in type A discs (pitch derived ‘C’) was more graphitic than the carbon matrix in type D discs (pyro ‘C’/pitch ‘C’). Still type D discs have shown the lowest wear because of the presence of strong interfacial bonding of pyro carbon with carbon fibre reinforcement, making the product resistant to wear. This led to the formation of smaller wear debris, which was quickly converted into thin, compact friction film. Hokao[21], *et al.* have also shown in their studies

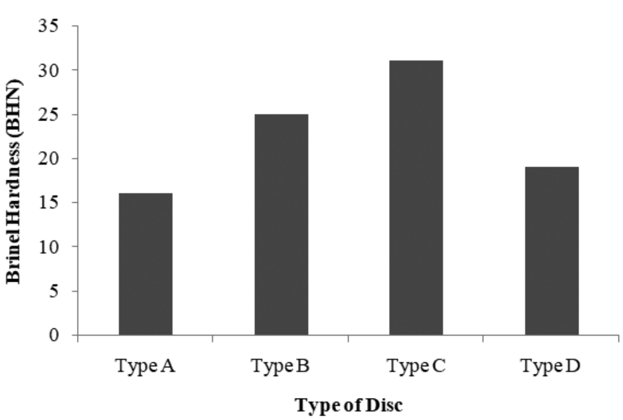

Figure 5. Hardness of C/C brake discs of Type A, B, C, and D.

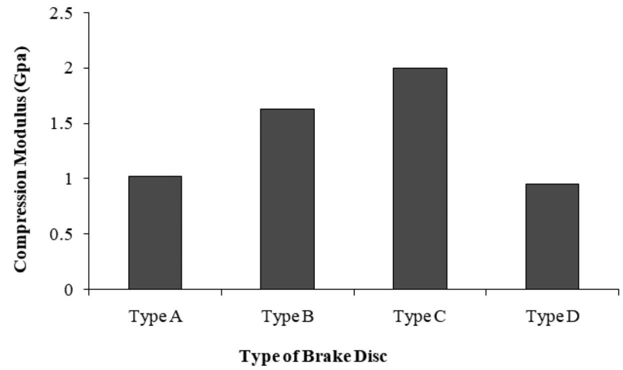

Figure 6. Compression Modulus of C/C brake discs of type A, B, C, and D.

on wear properties of graphitic and glassy carbon particulate composites, that the pure graphitic carbon did not give lowest wear, instead the optimum mixture of graphitic and glassy carbons showed the lowest wear. Soydan[20], *et al.* have reported that the toughness of the C/C brake discs was more effective in reducing the wear compared to its hardness.

In the present study as well, the most hard brake disc, the type C discs as shown in Fig. 5, did not show the lowest wear, whereas the type D discs which was capable of forming thin, compact friction film showed the least wear rate. Ming[22], *et al.* have reported that the brake discs having CVI/pitch hybrid carbon matrix showed more mass loss compared to the brake discs with CVI/resin hybrid carbon matrix. These results are contradictory to what is presented here. In fact the presence of hard, amorphous resin derived carbon had led to more wear compared to those having more graphitic carbon matrices.

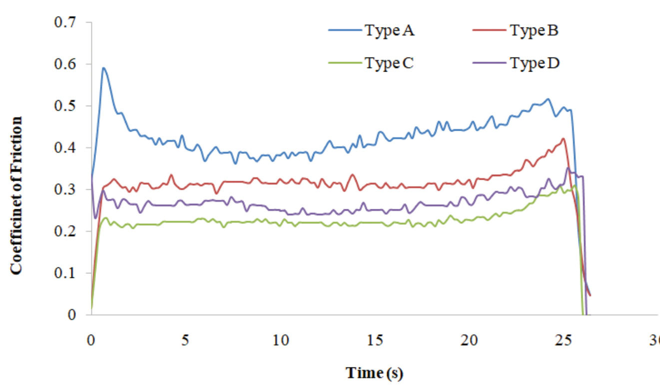

Figure 7. Coefficient of friction vs Time plots of C/C brake discs of type A, B, C, and D.

3.3 Coefficient of Friction

The coefficient of friction of C/C brake discs of type A, B, C and D are as shown in the Fig. 2. Comparison of coefficient friction vs time plots of these discs are as shown in Fig. 7.

As per the friction theory, coefficient of friction (μ) is given by the formula $\mu = F/N$

where F = Frictional force, N = Normal force

Bowden and Tabor[4] assumed that the contacting asperities would deform to the point of plastic flow and reach a contact pressure equal to the indentation hardness of the material. The real contact area Ar is determined from

$Ar = N/H$

where N = Normal force, H = Hardness.

From this relation, it is clear that for a given normal force, higher the hardness of the material, lower is the contact area and hence lower is the friction. So the harder material gives lower friction and softer one higher friction[4]. Gong[24], *et al.* have also related the coefficient of friction to the hardness of the C/C brakes doped with carbon nano tubes. Although hardness is an important factor, the tribo film or the friction film formed during the rubbing, influences the tribological properties significantly. So it is interesting to see how these parameters affect the friction coefficient of C/C brake discs.

It may be observed from the Fig. 2 that the COF of C/C brake discs is decreasing from type A to type C discs and then increasing in case of type D discs. The hardness (as shown in Fig. 5) and compression modulus values (as shown in Fig. 6) on the other hand are increased from type A to type C and then decreased in case of type D discs. In type A discs, the matrix part of the wear debris is graphitic, that helped in the formation of lubricating friction film. Still the coefficient of friction of this material is the highest (0.43). In type B discs, the matrix part of the friction film consists of both amorphous, resin derived and graphitic pitch derived carbons. The friction film formed is not as compact as that in the case of type A discs. However the friction coefficient is lower than the type A discs (0.34). Similarly the type C discs showed the wear rate similar to that of type A discs, but the COF (0.22) is the lowest. The trend in the COF of these three materials is not corroborated well with the nature of their friction films.

It may be observed that the COF of C/C discs of the type A, type B and type C has followed the reverse trend of their hardness. The type A brake discs have shown the lowest hardness and lower mechanical properties. This is due to its soft graphitic matrix, which has been derived from pitch[25]. Due to the softness, the real contact area would be more and the COF is high[4]. Unlike the other type of discs, type A discs have shown a sharp peak in the friction coefficient in the initial period of braking. This phenomenon is not desirable as it may lead to grabby brake and chances of wheel locking and skidding of the aircraft[26] may be possible with such brakes. The brake management system (BMS) in the aircraft manages the antiskid operations by maintaining the brake torque levels within the specified limits by manipulating the brake pressure during braking. The sudden rise in brake torque (high COF) especially at the starting of the braking event will be difficult to manage by BMS. Thus moderate COF of carbon brakes is always preferred.

On the other hand, type C brake discs are the hardest among the four types studied and showed higher mechanical properties and the lowest friction coefficient. Type C discs have three types of matrices, resin derived, pyro and pitch derived carbons. The resin derived 'C is harder[25-26] and the pyro carbon forms a strong inter facial bonding as it builds up slowly, atom by atom around the fibres[27]. This combined effect has made the composite not only harder but also stronger. The hardness and the COF values of type B discs were found to be in between the values of type A and type C discs. This is well understood as type B composite consists of carbon matrix partially derived from resin and the rest from pitch.

In comparison to type B, the type D discs have shown lower hardness but still maintained lower friction coefficient. As discussed in earlier section that the friction film characteristics of type B and type D discs were entirely different. In type D discs the friction film was most compact among the four types of discs studied and adhered to the rubbing surface strongly. This might have helped in efficient lubrication of the friction surfaces and lowering of COF. In spite of having the lowest wear rate and compact lubricating friction film, the COF of type D discs was still higher than type C discs. This may be because of its lower hardness compared to that of type C discs.

4. CONCLUSIONS

(a) Type of carbon matrix influences the friction and wear properties of C/C brake discs.

(b) Characteristics of friction film formed between the rubbing surfaces depend on the nature of the carbon matrix. The pyro carbon is the most effective in the formation of compact friction film whereas the resin derived carbon is the least effective.

(c) Carbon matrix with higher degree of graphitisation helps in the formation of lubricating friction film and reduces the wear rate. Apart from the degree of graphitisation, the strong interfacial bonding between the matrix and the reinforcement is also important in obtaining the low wear rate.

(d) The coefficient of friction of C/C brake discs is predominantly influenced by the hardness of the brake material. However, the cohesiveness of friction film also played a role in reducing the coefficient of friction.

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His contributions in the present study are conceptualisation and designing experiments and realisation of brake discs. He has also carried out testing and characterisation and analysed the results.

Dr P. Selvam obtained his MSc (Applied Chemistry) and PhD (Polymer Chemistry) from Anna University, Chennai, in 2001 and 2006, respectively. Presently, he is working as Scientist 'E' in the DRDO-Advanced Systems Laboratory, Hyderabad. He has been working in the area of high temperature composites for the development of densification technologies and establishment of facilities for carbon carbon (C-C), carbon silicon carbide (C-SiC) products for missile and aircraft applications.
In the present study, he has densified four different types of C/C brake discs through chemical vapour infiltration (CVI) and liquid pitch impregnation (LPI) process to derive primary and secondary carbon matrices.

Mr K.H. Sinnur obtained his BTech (Textile Technology) from Government S.K.S.J Technological Institute, Bangalore in 1984. He did MBA (Operations Management) from School of Management Studies, IGNOU, New Delhi, in 2010. Presently working as Scientist 'G' and Technology Director, High Temperature Composite Centre (HTCC) in DRDO-Advanced Systems Laboratory, Hyderabad. He has been working on the fibre architecture and development of carbon/carbon technology and products for aerospace applications.
In the present work he has monitored the work and provided valuable suggestions. He has also contributed in the analysis of test results.