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Effect of Weave Texture of Carbon Fabric on Mechanical, Thermal and Tribological Properties of Carbon/Carbon Aircraft Brakes

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Abstract Studied the effect of weave texture of the carbon fabric reinforcement on mechanical, thermal and tribological properties of carbon/carbon (C/C) aircraft brakes. High strength carbon fibre (T300) based carbon fabric (HSC) with coarse and compact weave configuration and spun yarn graphitized carbon fabric (SYG) with loose, bulky yarns having more open space were used. The microstructure of the composite showed that the carbon matrix was distributed around the fibres in much better manner in SYG based discs compared to the discs made with HSC fabric. SYG fabric based discs have shown higher inter laminar shear strength, thermal conductivity and better wear resistance, compared to the HSC based discs.

Keywords Carbon-Carbon composites, Aircraft brakes, Carbon fabric, Weave texture, Mechanical properties, Thermal properties, Friction, Wear

1. Introduction

Aircraft brake disc is the major application of carbon/carbon (C/C) composites [1-2]. C/C composite brakes are used in several military and commercial aircrafts. Unique combination of properties like high specific heat, thermal conductivity, retention of mechanical strength at elevated temperatures, good thermal shock resistance, light weight and excellent friction and wear characteristics make them ideal candidate for aircraft brake application [3]. Stable friction coefficient and low wear are the two key performance parameters of aircraft brakes. These tribological characteristics depend on several parameters, like the nature of reinforcement and carbon matrix [4-8], the process parameters [9-11], usage conditions [12-14], the environment [15, 16] etc. As far as the reinforcement is concerned, different grades of carbon fibres are used in various forms. The woven fabrics, chopped fibres, needle punched nonwovens are the most common. The configuration of the carbon fibre reinforcement is an important aspect, which influences various properties of C/C brakes, including the friction performance. There is not much information available in the open literature on this aspect. Julius Rotner [17] has studied how the plain and satin weave carbon fabrics affect the crack formation during the carbonization of carbon/phenolic (C/P) laminates. Studies have been carried out on comparison of carbon fabrics made with stabilized polyacrylo nitrile (PAN) based spun yarns, heat treated to 1100°C and PAN based carbon fibre continuous yarn fabric, on the mechanical, thermal and ablative properties of C/P composites. [18-19] L. M. Manocha et al [20] studied the carbon fibre weave pattern on the development of C/C composites. Jayshree Bijwe et al [21] and Rekka Rattan et al [22] have studied the influence of weave of carbon fabrics in polyether imide composites in various wear situations.

The present study aims at how the two commercially available carbon fabrics with distinctly different fabric textures influence the various physical, mechanical, thermal and tribological properties of C/C aircraft brake discs. PAN based carbon fabric made with T300 carbon fibres and PAN based spun yarn graphitized carbon fabric were used in this study. The studies were carried out on the actual size aircraft brake discs.

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2. Experimental

High strength carbon fibre (T-300) based carbon fabric (HSC) and spun yarn graphitized fabric (SYG) were used in the fabrication of two types of discs. The details of both types of reinforcements are given in Table 1.

2.1. Fabrication of C/C Brake Discs

Initially the carbon-phenolic discs were made from each type of carbon fabric prepregs made with resole type phenolic resin, by compression moulding. In case of type A discs, the phenolic resin was mixed with milled carbon fibre, whereas in type B discs, pure resin was used. The discs were carbonized up to the temperature of 1000°C, in an inert atmosphere (high purity nitrogen) and then densified using petroleum pitch (Ashland-240). The densification process involved three steps, impregnation with pitch, high pressure carbonization up to 700°C temperature under the pressure of around 1000 bar and graphitization above 2000°C. The densification cycles were repeated until the required density of 1.8 g/cc was achieved. The details of the discs are given in the Table 2.

Table 1. Details of the carbon fabric reinforcements used in this study

Parameter	Type of disc	
	Type A	Type B
Reinforcement	HSC	SYG
Weave configuration	8H-Satin weave	8H-Satin weave
Tex value of carbon fibre tow	200	100
Areal Density (g/sq.m)	380	300
Fabric Thickness (mm)	0.45	0.77

Table 2. Details of type A and type B discs

Parameter	Type A	Type B
Density (g/cc)	1.81	1.80
Open porosity (% by volume)	6.0	7.0
Fibre content (wt%)	47	36
Resin derived ‘C’ content (wt%)	33	28
Pitch derived ‘C’ content (wt%)	20	35
Rockwell Hardness (HRF)	95	86

2.2. Testing

2.2.1. Bulk Density

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

2.2.2. Open Porosity

Open porosity of the composite samples was measured using the Quanta Chrome make mercury porosimeter (Pore Master 33). The maximum pressure used was 30, 000 psi.

2.2.3. Optical Microscopy

The optical microscopic images were taken on OLYMPUS make GX51M optical microscope.

2.2.4. Scanning Electron Microscopy

ZEISS make scanning electron microscope was used for microscopic analysis of carbon fabrics, fractured surfaces of test specimens and the friction film formed on the discs in DOD testing.

2.2.5. Raman Spectroscopy

Raman spectra were recorded on JY T-64000 spectrometer. The configuration has a provision for triple subtractive, single spectrograph and remote probing with confocal micro and macro sampling accessory. 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 of about 2 µm and the laser power of 25 mW was used.

2.2.6. Thermal Conductivity

Thermal conductivity was calculated from room temperature to 1200°C by using the following formula.

$$T.C = T.D \; X \; Cp \; X \; \delta$$

Where
T.C - thermal conductivity
T.D – thermal diffusivity
Cp – specific heat at constant pressure
δ - density of the sample

Thermal diffusivity was measured as per ASTM E 1461 on Netzsch make LFA-427 laser flash equipment from room temperature to 1200°C on the samples having the dimensions of 12.5 mm diameter and 2.5 mm thickness. It was measured on the composite samples in the directions parallel and perpendicular to the carbon fabric. Specific heat values reported in the literature were used in the calculation of thermal conductivity.

2.2.7. Tensile Test

The tensile strength test was conducted on dumbbell shaped specimens of dimensions 120 mm X 10 mm X 6 mm on Universal Testing Machine (UTM). Total six number of samples were tested and the average value is reported. The specimens were tested at a cross head speed of 1 mm/min.

2.2.8. Inter Laminar Shear Strength (ILSS)

Inter Laminar Shear Strength (ILSS) was measured as per ASTM D 2344 using the test specimens of dimensions 65 mm X 13 mm X 8 mm on UTM. The test was carried out at a cross head speed of 1.5 mm/min.

2.2.9. Hardness

Hardness of C/C composite samples was measured on ‘F’ scale of Rockwell hardness tester using 1/16” ball indenter with an applied load of 60 kgf.

2.2.10. Dynamometer Testing

The coefficient of friction and wear rate of C/C brake discs were evaluated using disc-on-disc (DOD) brake dynamometer with variable inertia. The testing was carried out using a pair of discs consisting of a rotor and a stator simulating aircraft normal and over load brake energy conditions corresponding to one interface. A C/C rotor mounted on a rotating axle on which the inertia wheels were engaged was rotated to the required rpm corresponding to the peripheral velocity of 41 m/sec in case of NL energy, 43 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 seconds. The brake torque vs time was recorded and the average torque and friction coefficient for each run was calculated. Total 50 runs consisting of 45 normal and 5 over load brakings were carried out for each type of discs. The friction coefficient and wear rate were calculated, after each block of testing (9 NL+1 OL) and the average values of 5 blocks were considered.

3. Results and Discussion

3.1. Microstructure of the Reinforcement

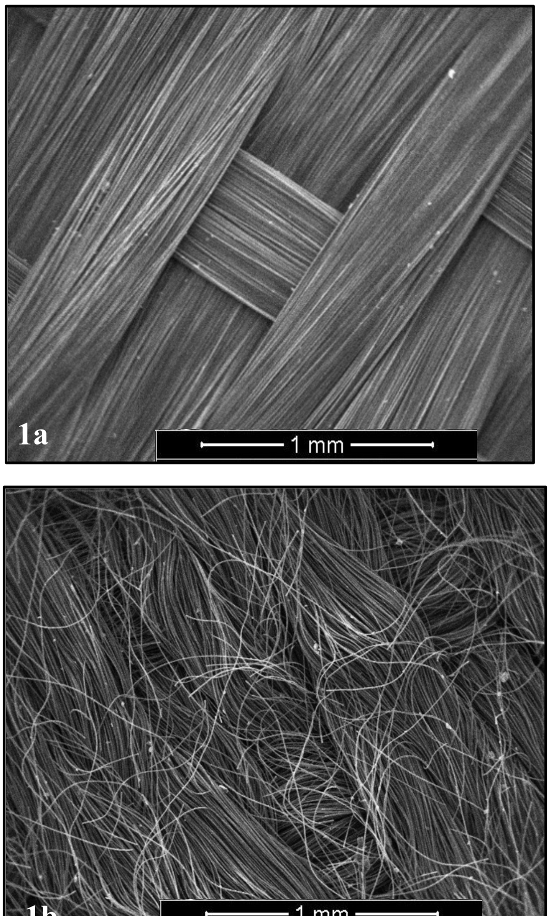

Figure 1. SEM images of (a) HSC and (b) SYG fabrics

The SEM images of both types of carbon fabrics are shown in the Figure 1. It is observed from the images that in HSC carbon fabric, the carbon fibre tows are straight and more closely packed. The texture of the carbon fabric is coarse and compact. Whereas in SYG fabric, the fibre tows are loose and curved. Some of the fibres are completely disoriented in the plane and also out of plane. This fabric has finer texture compared to HSC fabric. It is bulkier with lot of free space within the fibre tow. In case of HSC fabric, the kinks at fibre tow cross over points are large and distinctly visible compared to that in SYG fabric.

The microstructure of these two types of carbon fibres also differ with respect to the degree of graphitization. The Raman spectra of these fibres is shown in the Figure 2. It is evident from the spectra that, the D/G ratio (the ratio of intensity of disorder band (D) to the graphite band (G)) is higher for the HSC fibre compared to SYG fibre. It is due to the differences in heat treatment temperatures experienced by the two types of carbon fibres at the time manufacture. The T300 fibre form which the HSC fabric was made, was carbonized at temperatures less than 1500°C, whereas the spun yarn fibres are graphitized.

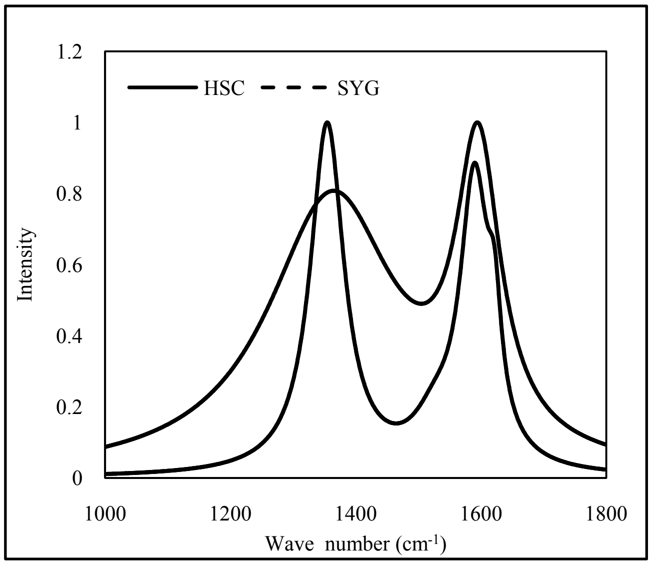

Figure 2. Raman spectre of HSC and SYG fibre

3.2. Microstructure of the Composites

Optical microscopic images of C/C brake discs of type A and type B disc samples are shown in Figure 3. It may be observed from the figure that, the fibre matrix bonding in type B discs is looking much better than that in type A discs. This is because, in type B discs, there is more free space around the fibres within the tow compared to the more compact fibre tow in HSC fabric. This facilitates the better access of the matrix around the fibre. It can be well observed that, in type A discs the large chunks of resin derived carbon is accumulated at the fibre tow cross over points. This portion was reinforced with milled carbon fibre and looks like a segregated region. In case of type B discs the resin derived carbon present at the cross over points, is reinforced with the individual carbon fibres and do not look like an isolated entity.

3.3. Mechanical Properties

The tensile strength of type A disc is about 15% higher than that of type B discs (see Figure 4). The higher tensile strength of type A discs is due to higher fibre content compared to the type B discs. On contrary, the ILSS of type B discs is about 27% higher than that of type A discs. This is because of the good bonding between the fibre and matrix in type B discs. At the same time, some of the fibres protruded out of plane might have contributed to the higher ILSS value [18]. These phenomena are quite apparent in the failure modes of the samples under tensile load (see Figure 5-6). In type A disc samples, sever delaminations and fibre pull out are observed, whereas a complete contrast behaviour is observed in type B discs. The fracture surface of the type B discs shows few cracks, only in a limited area. These cracks traverse more torturous path as the fibres are curved.

Otherwise most of the fracture surface is compact. Fig. 6a shows the severe fibre pull out in type A discs. In type B discs also the fibre pull out is observed but to lesser extent compared to that in type A discs. The most striking feature in Fig 6b is the extensive flow of matrix in the fractured surface. This may be due the excessive straining of the matrix during the fracture, indicating the strong fibre matrix interface bonding.

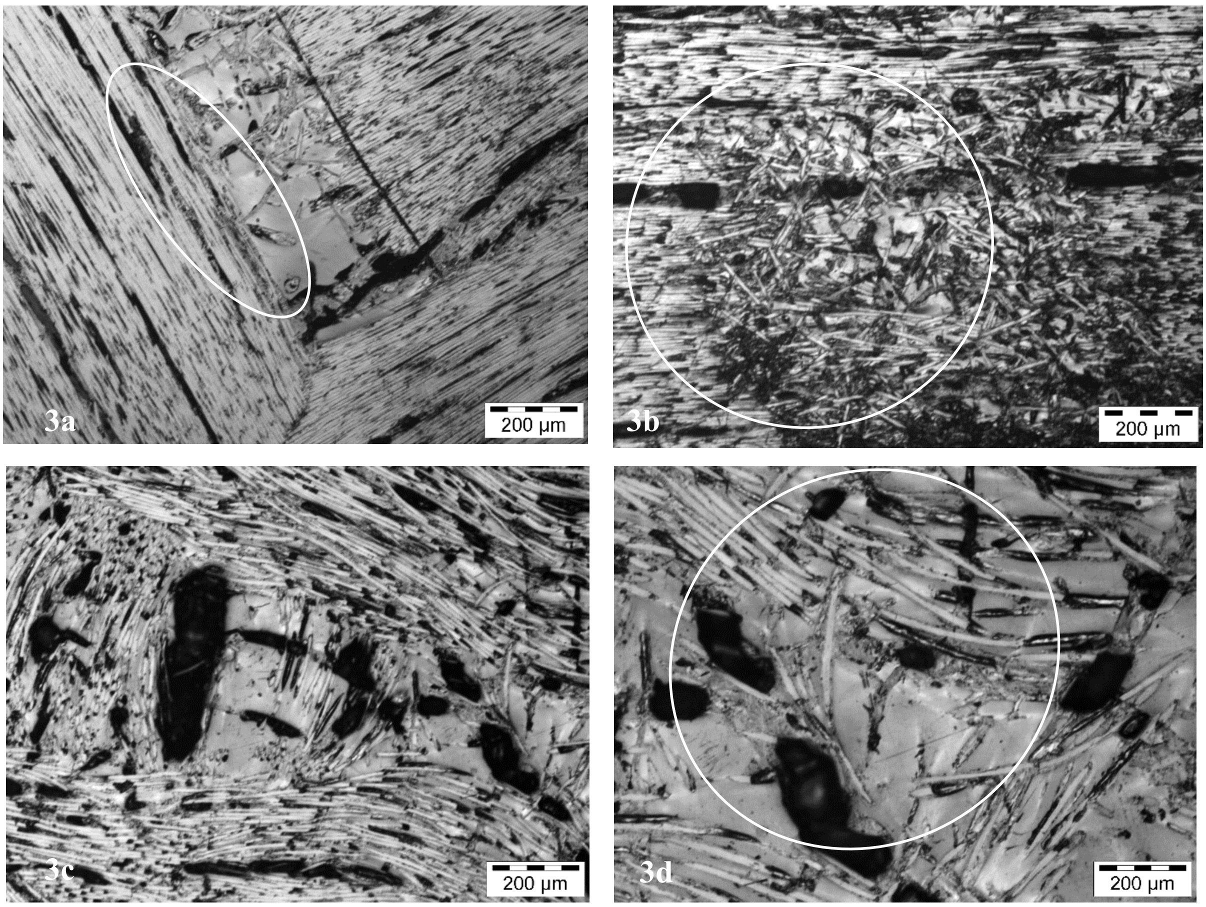

Figure 3. Optical micrographs of type A disc 3(a), 3(b) and type B disc 3(c), 3(d)

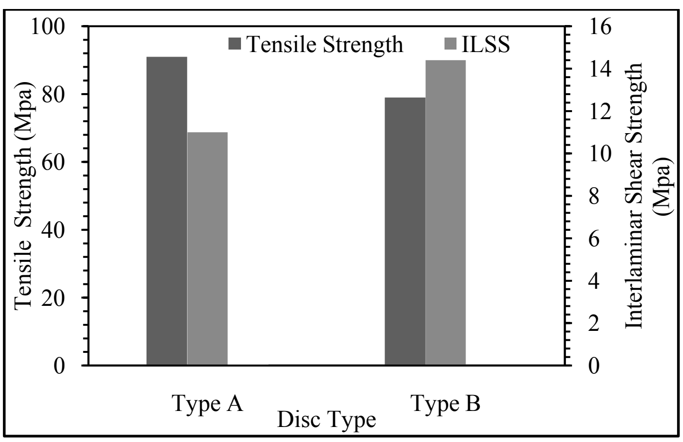

Figure 4. Tensile strength and inter laminar shear strength of type A and type B discs

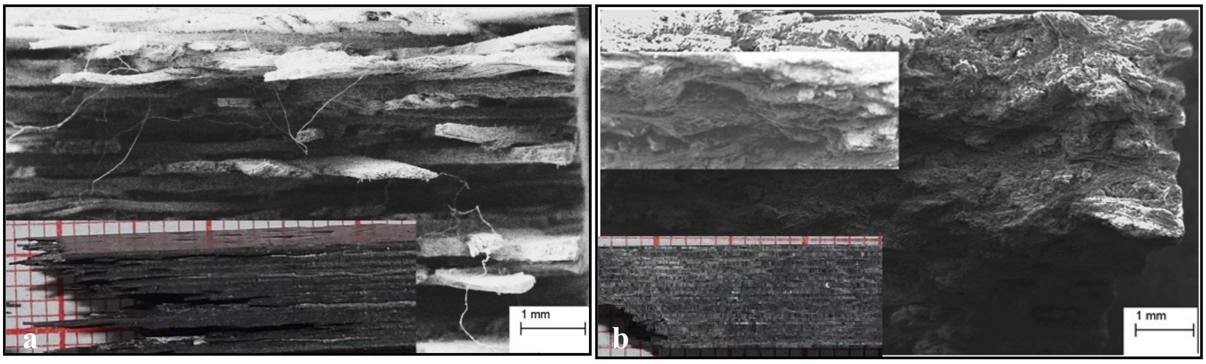

Figure 5. Fracture surfaces of (a) type A disc and (b) type B disc

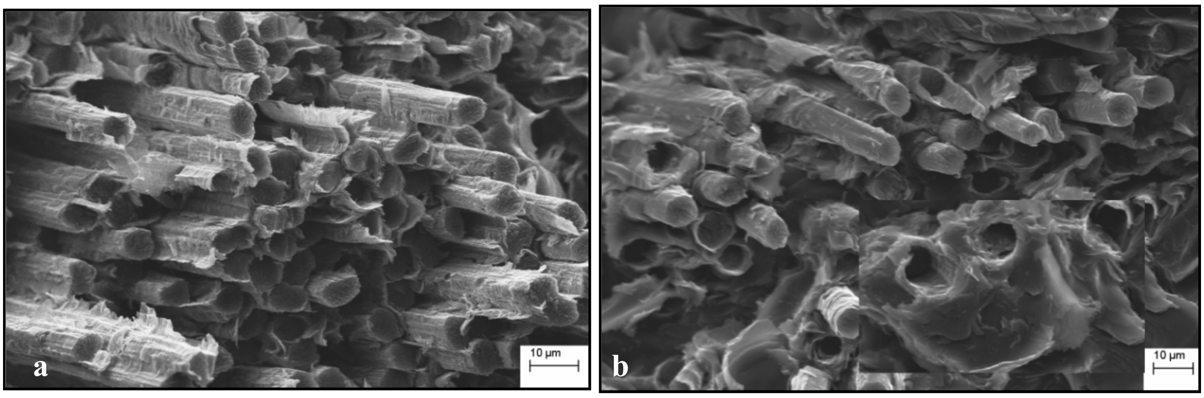

Figure 6. Micro structure of fractured surfaces of (a) type A disc and (b) type B disc

In the real usage, the discs are subjected to shear forces during the braking. During the handling, there is always a possibility for the discs to experience the impact loads. Resistance to failure under such loads is very important. Sever chipping on the rubbing surface was observed in type A discs during the flight use (Figure 7a), whereas no such chipping was observed in type B discs. Figure 7b shows the smooth friction surface of type B discs.

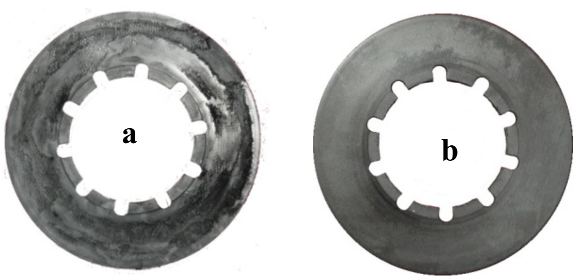

Figure 7. Friction surface of type A (a) and type B (b) stator discs after flight use

Fig. 8 also shows the nature of the impact damages in type A and type B discs. The damage in the discs is only localized in type B discs, whereas in type A discs the damage is extended and the loose fibres are visible.

These observations demonstrate the relative compactness of these discs.

3.4. Thermal Conductivity

Thermal conductivity of type A and type B discs in both parallel and perpendicular directions to the carbon fabric reinforcement, from room temperature to 1200°C are shown in Figure 9.

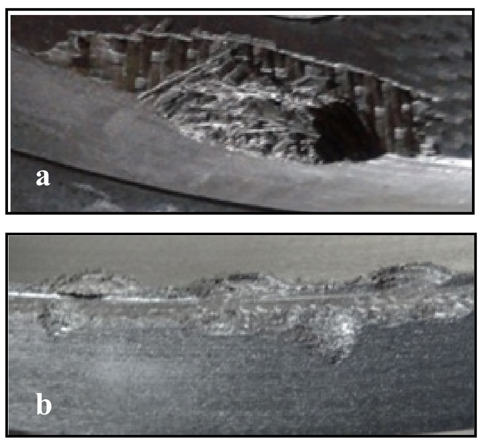

Figure 8. The damage in the (a) type A and (b) type B discs

Thermal conductivity of type B discs is higher than that of type A discs in both parallel and perpendicular directions to the fabric layers. Even though the fibre content in type B discs is lower than that in type A discs, shows higher thermal conductivity. This may be because, the carbon fabric in type B discs is graphitized (see Figure 2). The higher content of pitch derived ‘C’ matrix and the protruded carbon fibres across the thickness might have contributed to the higher thermal conductivity in the direction perpendicular to the fabric layer.

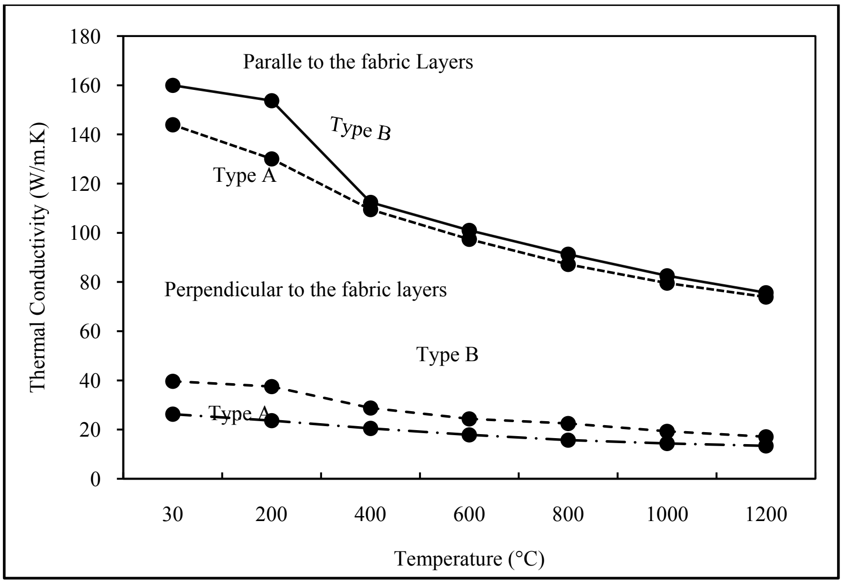

Figure 9. Thermal conductivity of type A and type B discs

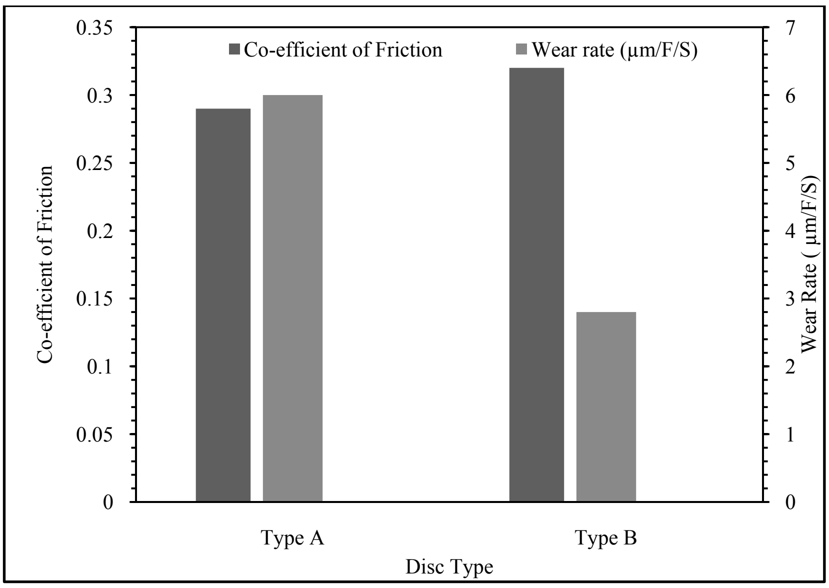

Figure 10. Coefficient of friction and wear rates of type A and type B discs tested on Disc-on-Disc brake dynamometer

3.5. Tribological Properties

The coefficient of friction and wear rates of the two types of discs are shown in the Figure 10. The coefficient of friction of type B discs is about 10% higher than that of type A discs. The lower hardness value of type B discs and also the presence of protruded fibres might have contributed to this higher coefficient of friction. On the other hand, the wear rate of type B discs is more than 50% lower than that of type A discs. The big reduction in the wear rate of type B discs is due the better friction film formation compared to that in type A discs. From the Figure 11, it is evident that, the friction film of type B discs is more compact compared to type A discs. The friction film in type A discs is broken down at several places exposing the large portion of the disc surface. The poor friction film formation in this case might be due to the coarse texture of carbon fabric and less compact composite.

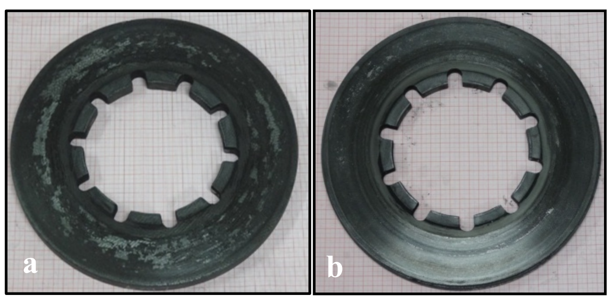

Figure 11. Friction surfaces of (a) type A disc and (b) type B disc

Figure 12a shows that, how the large number of carbon fibres as an unit present in the friction film formed out of wear debris. This looks like a carbon fibre tow has chipped out from the friction surface as a chunk. Bigger resin derived carbon matrix pockets might have also chipped out. Wear debris having such big chunks, is difficult to convert into smooth and compact friction film, which is essential for effective lubrication and reduction of the wear. In contrast, in the friction film of type B discs, only small sized carbon fibres are found in few numbers. This is because, matrix is more uniformly distributed around the fibres in case of type B discs, forming the stronger fibre matrix interface. More graphitic carbon fibres in SYG, which can be easily sheared compared to those carbonized in HSC fabric, might have also worked in favour of the formation of good friction film.

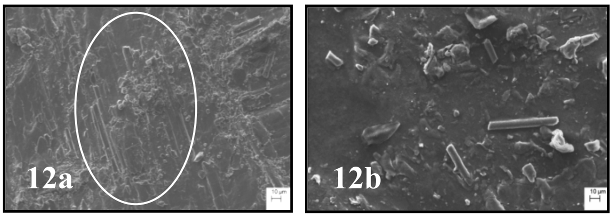

Figure 12. Microstructure of friction film of (a) type A disc and (b) type B disc

4. Conclusions

- The texture of carbon fabric affects the various mechanical, thermal and frictional properties of C/C aircraft brakes.
- The bulky carbon fabrics with more open spaces like spun yarn carbon fabric forms better fibre-matrix interface compared to the compactly woven fabrics. This affects the mechanical properties and mode of fracture of C/C composites. The C/C composite discs made with compactly woven fabrics (HSC) are less compact compared to the SYG based discs. The damages in the SYG based discs are more localized due to its compact nature compared the HSC based discs.
- The thermal conductivity in SYG based discs is higher in both parallel and perpendicular direction due to more graphitic nature of the fibres. The protruded fibres also contributed to the higher thermal conductivity of the discs across the thickness.
- The wear resistance of the discs is strongly affected by the texture of carbon fabric. The coarse and compact textured HSC fabric based discs showed higher wear rates compared to the carbon fabric made with bulky, opened up tows with fine fabric texture.

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