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Climate Based Performance of Carbon-Carbon Disc Brake for High Speed Aircraft Braking System

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ABSTRACT

Carbon composite brake discs are lighter, economical, and have excellent high energy friction characteristics. These have twice thermal capability compared to steel, remain unaffected by thermal shocks and mechanical fatigue. These are highly useful in emergency breaking situations. Prior to this work, two dimensional (2D) reinforced carbon composite laminates were prepared through pitch impregnation process. In an effort to protect the exposed non frictional surface from high temperature service degradations, multilayered ceramic coating systems were developed on 2D composite. Oxidation studies have been carried out on these systems viz., *C-SiC, C-SiC-MoSi*$_2$-*Al*$_2$*O*$_3$ and *C-SiC-B*$_4$*C*. These were performed both in dynamic and static conditions up to 1200 °C in 60 per cent humid climate. The hardness, surface topography, developed phases and integrity of layers on the samples at various stages of the experiment have been characterized and analyzed. It was observed that *C-SiC-B*$_4$*C* system performs well in the oxidizing environment.

Keywords: Friction brakes, heavy vehicle sectors, aircraft braking process, carbon -carbon disc, thermo-environmental protection, thermal wear, multilayer systems, plasma spraying

1. INTRODUCTION

The purpose of friction brakes is to decelerate a vehicle by transforming the kinetic energy of the vehicle to heat, via friction, and dissipating that heat to the surroundings. Automotive braking systems are normally made of steel or grey cast iron and are then paired with polymer-composite pads[1]. These types of materials are suitable for use in braking systems with moderate loads with a limited temperature capability, where they exhibit a relatively high and stable friction coefficient, a low-wear rate and are quiet during operation[2]. However in heavy vehicle sectors e.g., racing cars, large automotive carriers, high speed train, fighter aircrafts and military systems require braking systems that provide more braking power than conventional braking systems. Braking consistency means safety and also performance enhancement for heavy vehicles. Accordingly, advanced materials are being introduced into these braking systems, for example, carbon-carbon (C/C) composites[3,4], which can provide more friction and can operate at higher temperatures. Numerous accidents are caused by trucks whose brakes have overheated while descending a hill road and are subsequently unable to stop. For example, the stopping distance of a 20 ton truck after a descending a 10 per cent incline for 5 km at 60 km/h is nearly 80 m with cast iron brakes. Calculation shows the stopping distance can be reduced to only 25 m with carbon brakes. Carbon-carbon brake can significantly lowers the load per axle of high speed trains and decreases the energy consumption. It has a major effect in prolonging the life of the track. The C/C combinations are more commonly used in aircraft brakes where landing speeds are more than 250 km/hr, landing weights are more than 1,00,000 kgs and brake energies are 10 to 50 million Joules[5,6]. This composite also performs well in rejected take-offs[7,8]. Figure 1(a) illustrates the factors involved in an aircraft braking process. Indeed for some larger aircraft, a fully loaded landing and takeoff may not be possible without the utilization of carbon-carbon brake. These are because of outstanding properties of carbon-carbon composites viz., directional high-temperature heat dissipating qualities, absence of fatigue as understood in metals, four times lighter than the steel and copper bases used in low performance aircraft brakes, high thermal capacities (twice of steel), stable coefficient of friction and a low wear rate over a wide range of sliding conditions, particularly temperature that can exceed 1000 °C[9,10].

The graphitic carbon composites provide both frictional and structural supports within the disc brake simultaneously. Associated carbon fibres offer high specific stiffness and strengths in comparison with steel. The use of C/C in aircraft brake system has been traced back to 1974 and it is about 1982 where further research led to standard installation of carbon brakes in about 50 aircraft types. For example, commercial aircraft, like the Airbus 319, MD-11, Boeing 767 to Boeing 777; military aircraft, like the F-15 to F-22, and joint strike fighter like Mirage 2000 use C/C brakes[5, 6,11]. The technical features of C/C as friction materials for aircraft brakes are as follows;

(i) capacity for dissipating a extreme ablation heat (20.000

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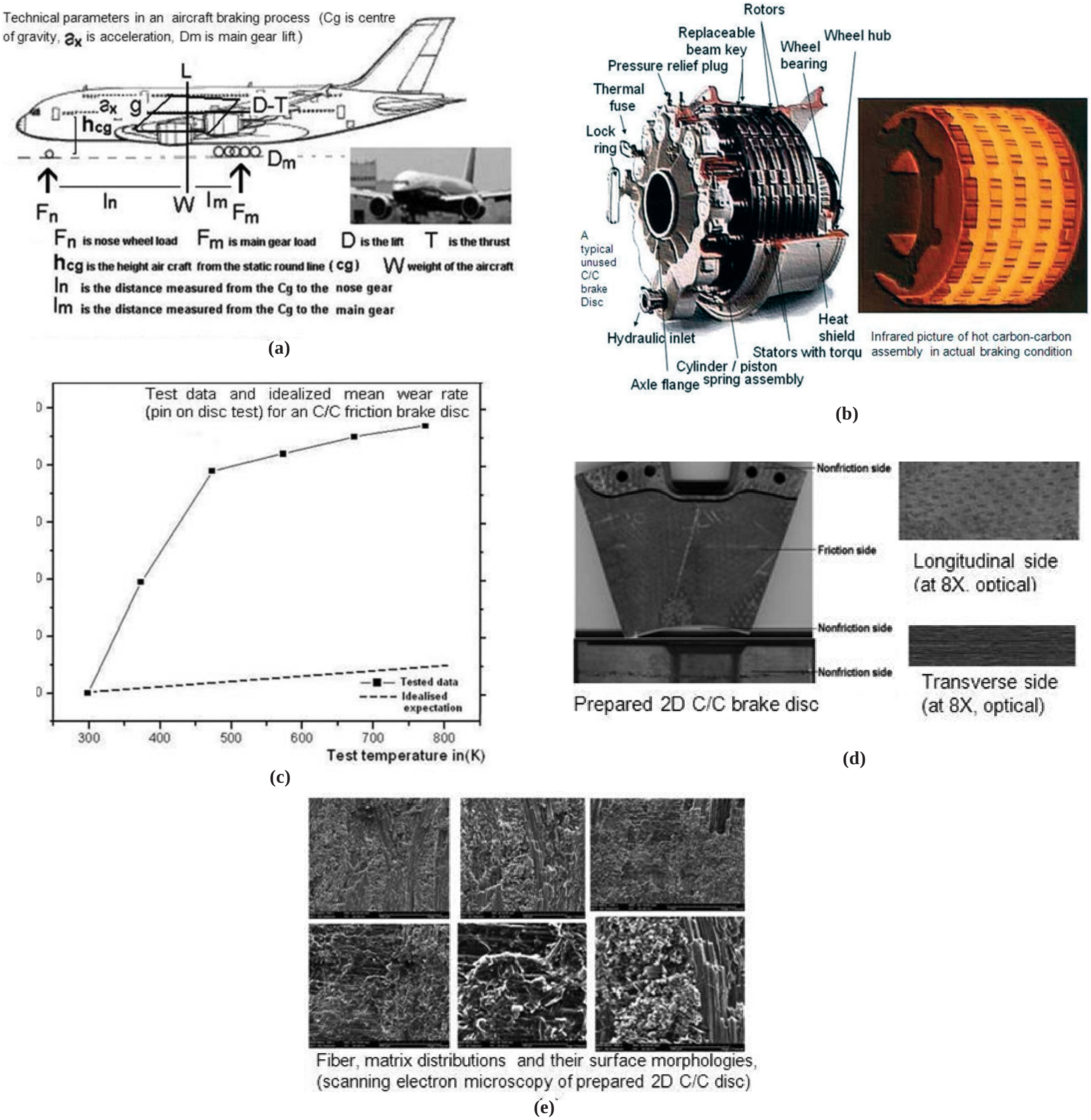
Kcal/Kg),

(ii) specific weight is from 1.7 to 1.9 Kg/dm^3,

(iii) friction coefficient is as 0.3, and

(iv) significant dimensional stability at very high temperatures (i.e., small dilatation coefficient, max 2x10^{-6} v.s.10^{-5} for steel).

Carbon discs are lighter, safer and economical for long term use **(**deliver an average of 2,500 landing cycles; an Airbus company data**)**. Such high speed brake applications require the sliding interfaces to convert about 4500 J cm^{-2} of kinetic energy per unit area to heat in approximately 30 s. In addition, the thermal cycling promotes cracking in uncoated carbon-carbon which can result in accelerated wear and oxidation[12]. Further, this energy when absorbed within a short interval of 15 s to 18 s leads to extremely high rate of heat generation on the brake surfaces and steep thermal gradients across the friction material brake pads, of more than 1000 °C per cm and brake bulk temperatures in excess of 1000 °C Fig.1(b). Although the properties of carbon-carbon make it the practical material for ultra high temperature friction applications, its



(a)

(b)

(c)

(d)

(e)

Figure 1. Aspects of aircraft braking process, the C/C brake disc, wear requirement of C/C brake disc and its internal structures.

useful lifetime are restricted by the susceptibility to oxidation. Besides the bulk high temperature, chemisorptions of oxygen and physically adsorbed water also play a detrimental role for premature degradation of carbon brakes[13-16]. Accelerated oxidation weakens the material and increases the wear rate. To have a high degree of structural stability and longer life proper anti-oxidation (A/O) coatings are necessary on non-friction surfaces of heat sink discs[17-21].Thus to have easy maintenance, improve emergency breaking efficiency and provide intended longer life a set of multilayer coating systems were developed on 2D -reinforced carbon composite laminates prepared through pitch impregnation process. The oxidation studies were carried out to evaluate a suitable combination for the required thermo-environmental protection.

2. EXPERIMENT

Figure 1(c) presents wear rates for an as-prepared C/C friction brake disc as well as an ideal wear profile obtained from an equivalent high density graphite upto 800K which stays unreliable for thermo-structural conditions observed for high speed brake applications. Achieving the ideal wear rate state is possible only when a suitable protection is developed on a bare C/C component. In an effort to protect the exposed non frictional surface from oxidation and to improve their service life, both silicate and borate forming ceramics viz., SiC, $MoSi_2$, Al_2O_3, B_4C were used on 2D composite to develop a set of multilayer systems. Representative sample substrates of size 12.5 mm x 12mm x 18mm were cut from the prepared 2D carbon–carbon composite panel having coal tar pitch resin with required quantities of non-graphitizing resins as matrix precursor with high and uniform ($0^o/90^o$) T600 carbon fibres mat with 550µm width fibre runs. The average density of the composite was 1.816 g/cm^3 with local hardness varying from 537Hv1 (20 s) as minimum to 787 Hv1 (20 s) as maximum. The average hardness values were varying between 719 to 743 Hv1. After being hand-polished using 80 grit SiC paper, these specimens were ultrasonically cleaned using acetone and dried at 100 °C for 2 h. The silicon carbide conversion coating was performed at 1600 °C for 2 hr. It was followed by development of $MoSi_2$-Al_2O_3 and B_4C coating on these SiC coated C/C substrate through air plasma spraying. The dynamic and isothermal oxidation testing were carried out up to 1200 °C in thermal analysis system capable of measuring the remained mass in the desired time interval. The system was having an open air (air is saturated with 60% moisture at a room temperature) circulated furnace of size 120 mm diameters and 200 mm length under a flow rate of 120 ml/min. The furnace was capable of achieving 1200 °C in 35-50 min and it was controlled through a programmable controller. The dynamic test was carried out at a rate of 40 °C per minute to replicate expected service environments. The low magnification microstructure of the as prepared C/C composite, coated composite before and after oxidation test were observed using a stereo microscope. The phase contents of samples including tested one were determined using the Philips Xpert pro diffractometer having accelerator detector at 40 KV-30 amps power. The thickness of the coating were determined through an optical microscope BX60M of Olympus using 'image-Pro plus v5.0' software. Archimedes principle was used to find the density of the samples. Oxidation studies have been carried out on these systems viz., C-SiC, C-SiC-$MoSi_2$-Al_2O_3 and C-SiC-B_4C. These were performed both in dynamic and static conditions up to 1200 °C. The hardness, surface topography, developed phases and integrity of coatings on the samples at various stages of the experiment have been characterized and analyzed.

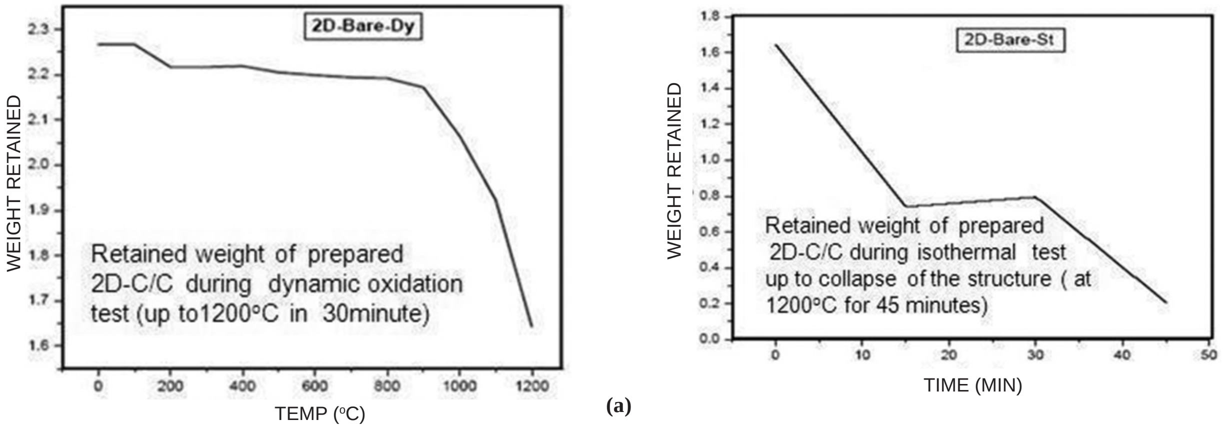
3. RESULT AND DISCUSSION

The feature of a sector of as-prepared 2D C/C brake disc with both friction and non friction side has been presented in Fig. 1(d). The upper image of Fig.1 (d) exhibits the exterior diameter portion of the brake disc section. Figures 1(d) also presents the longitudinal and transverse cross sections of the as-prepared 2D C/C respectively. The scanning electron microscopy of the composite depicting the surface features are presented in Fig. 1(e). The microscopic examination of longitudinal side of the brake disc showed the presence of a number of inherent and inevitable defects sites. These were shallow depths near the fibres knot regions, existence of few micro cracks and uneven matrix regions. However these defects were low because of presence of large volume fraction of fibres. Along transverse side the volume fractions of fibre were low compared to that of longitudinal side. The transverse section was having extensive matrix cracks with presence of ply delaminations. The weight losses observed during the oxidation test were up to 60 wt% at 1000 °C and 91 wt% at 1200 °C [Fig 2(a)]. In both exposure cases the entire C/C structures were collapsed with separation of several layers of the composite. Transverse oxidation damages were too high compared to the longitudinal one. Thus to protect the 2D composite from oxidation coating combination viz., 2D C/C-C-SiC, 2D C/C-C-SiC-$MoSi_2$-Al_2O_3 and 2D C/C- C-SiC-B_4C were studied. The measured densities and thicknesses of the coatings developed on the composite samples are being presented in Table 1.

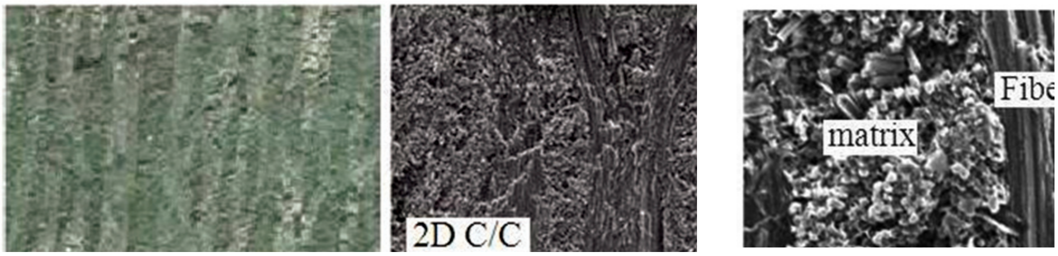
Features of SiC coating on 2D C/C before and after oxidation, weight changes in both dynamic and isothermal at 1200 ^{o}C heating , phases present in both cases having presented in the Figs. 2(b) and Tables 2 and 3. Before oxidation the surface was little uneven due to differential formation of SiC on the composite. After oxidation the surface was smooth but most of the samples showed layer delamination. There was no weight loss or significant gain up to 1200 °C dynamic heating while at isothermal treatment for 2 hr resulted in 32.5 % weight loss. At 1550 °C isothermal treatment for one hour the weight loss was 42 %, delaminations and extensive transverse damages were observed in samples. At 1200 °C isothermal treatment the weight loss was steady and appreciable more. Table 2 shows

Table 1. Density and thickness of coatings on C/C

Coating type on C/C	Thickness (in µm) on the sample	Density(gm/cc) of sample
SiC	460	2.06
SiC-$MoSi_2$-Al_2O_3	620	2.10
SiC-B_4C	670	1.94



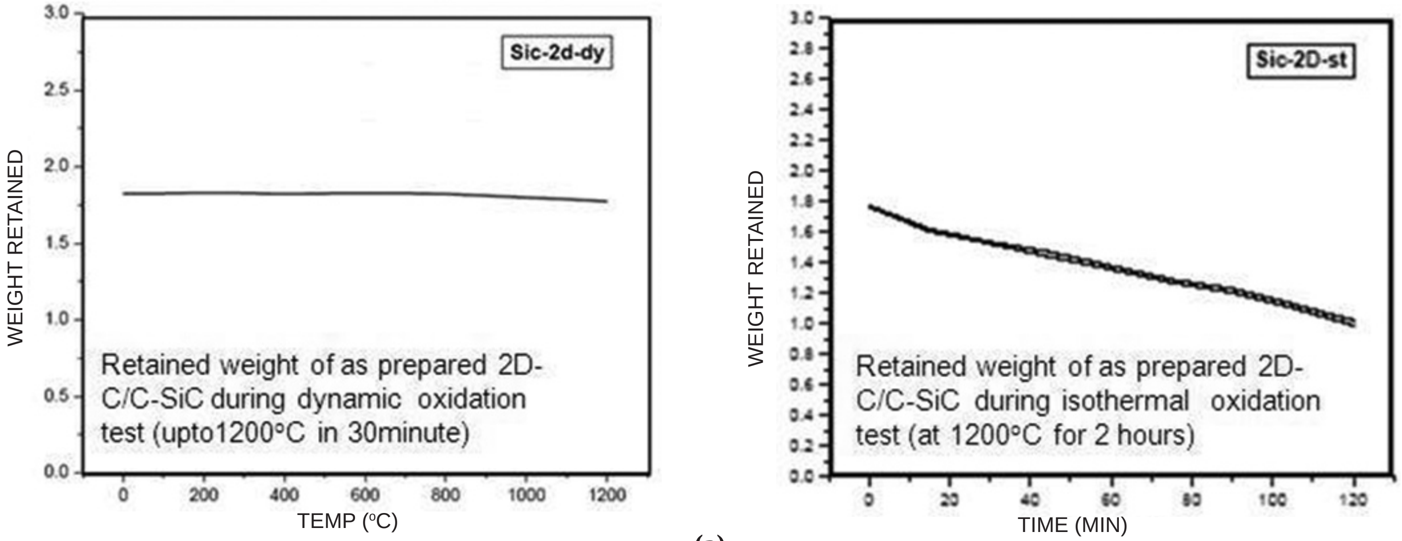
(a)



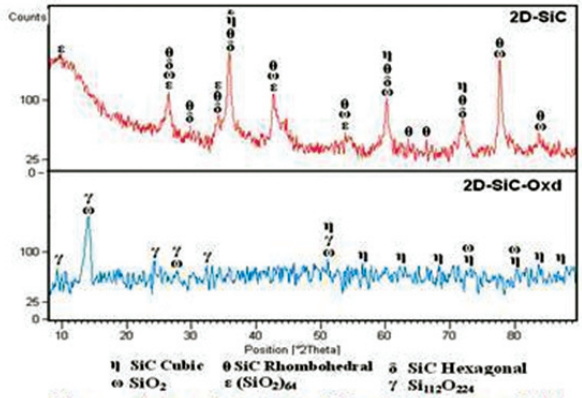
Stereo-macrograph of 2D C/C- *SiC* before oxidation test (8X)

(b)

Figure 2. (a) Heat exposure profile for the prepared 2D-C/C; and (b) *SiC* coated 2D-C/C.



(a)



(b)

Phases observed in X-ray diffraction pattern of SiC coating on 2 D C/C; Upper: before oxidation and lower: after oxidation

(c)

Stereo-macrograph of 2D C/C-SiC after oxidation test (8X) depicting the damaged surfaces & distorted geometrical features

Figure 3. Heat exposure profile for *SiC* coated 2D-C/C composite.

the presence of 98 wt% *SiC* along with 2wt% complex *Si-O* before oxidation. After 1200 °C for 2.5 hr the *SiC* and *Si-O* contents were 28 wt% and 72 wt% respectively.

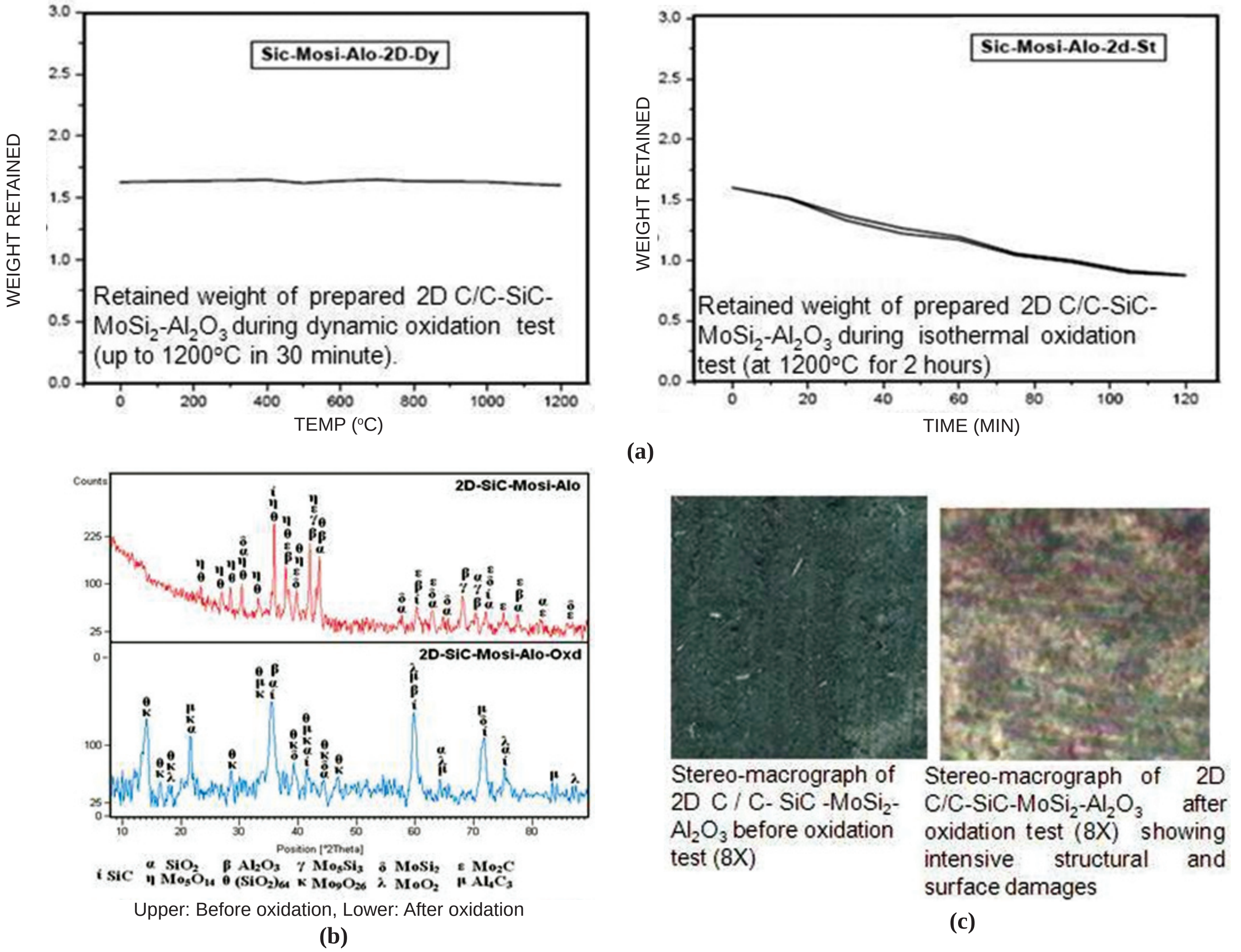
As observed in Fig. 4 oxidation damages were significant at 1200 °C for composite samples with $SiC\text{-}MoSi_2\text{-}Al_2O_3$ coatings. The heat exposed samples were brittle and extensive delaminations of the coated composite were observed. The total weight loss was about 38 % Fig. 4 (a). The slope of profile obtained for $SiC\text{-}MoSi_2\text{-}Al_2O_3$ coating was more compared to that of *SiC* coating. The significant weight loss in case of $MoSi_2$ based coating was due to the presence of intermediate molybdenum oxides (Mo-O) as oxidation products having inherent unfavorable properties of being volatile above 500 °C and having variable thermal expansion coefficients Fig. 4 (b).

Table 2. Quantified X-ray pattern as obtained for 2D C/C- *SiC* before oxidation

Ref. code	Score	Compound Name	Scale factor	Chemical formula	SemiQuant [%]
73-1665	41	Moissanite	0.692	$Si\,C$	7
85-0335	20	Quartz low	0.196	$Si\,O_2$	2
73-2082	25	Moissanite	0.385	$Si\,C$	12
73-2086	25	Moissanite	0.652	$Si\,C$	79

Table 3. Quantified X-ray pattern as obtained for 2D C/C- *SiC* after oxidation

Ref. code	Score	Compound	Scale factor	Chemical formula	SemiQuant [%]
82-1561	13	Silicon Oxide	1.012	$Si\,O_2$	19
88-1154	4	Zeolite SSZ-31	2.400	$Si_{112}\,O_{224}$	53
75-1541	2	Moissanite	0.507	$Si\,C$	28



Upper: Before oxidation, Lower: After oxidation

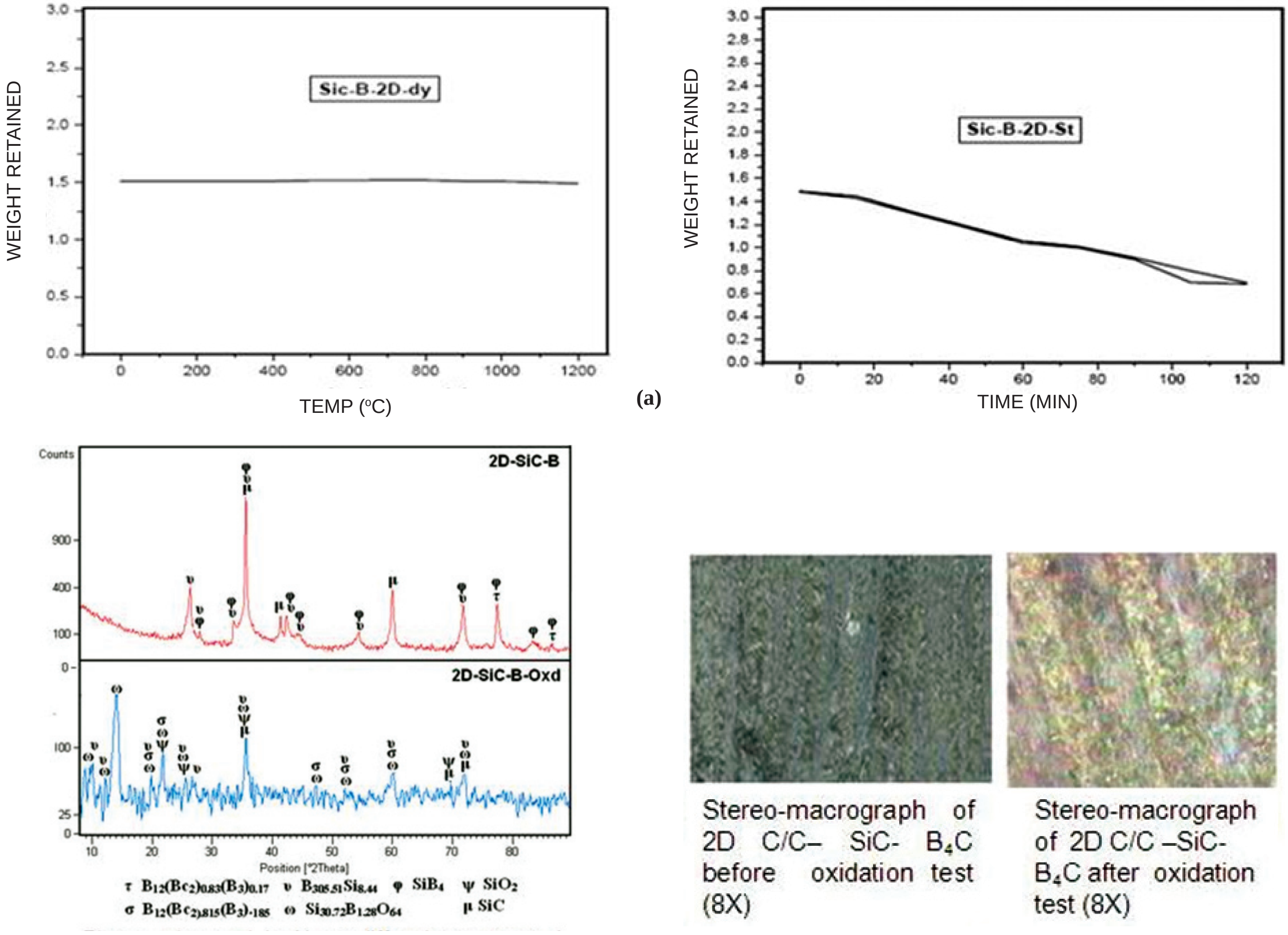
(b)

Stereo-macrograph of 2D C / C- SiC -$MoSi_2$-Al_2O_3 before oxidation test (8X)

Stereo-macrograph of 2D C/C-SiC-$MoSi_2$-Al_2O_3 after oxidation test (8X) showing intensive structural and surface damages

(c)

Figure 4. Heat exposure profile for $SiC\text{-}MoSi_2\text{-}Al_2O_3$ coated 2D-C/C composite.



(a)

Upper: Before oxidation, Lower: After oxidation

(b)

(c)

Figure 5. Heat exposure profile for $SiC\text{-}B_4C$ coated 2D-C/C composite.

The differential thermal expansions assisted in generation of further cracks in the coating Fig. 4 (c). Figure 5 present the surfaces of SiC-B_4C coated samples 'before and after' oxidation. In both cases the surface appearance was good and samples were intact. However the coating was partially protective for this 2D C/C. The structure didn't collapse. The geometrical shape was maintained although there was presence of micro holes and the weight loss was 30 % Fig. 5 (a). There were no delaminations of the composites and the $SiC\text{-}B_4C$ coating was intact even after the exposure tests. The protecting nature of this coating was undermined due to presence of unavoidable few shallow defects at fibre-matrix interfaces even after the coating was completed.

From weight change data after heat exposures, macro-structural observations, change of surface roughness and X-ray diffraction patterns, phase formations on the coated samples 'before and after' the oxidation, it was observed that the oxidation behaviour of the coated samples varies strongly on the nature of oxide layer developed on the surface by oxidation, their sustainability, crack sealing ability of the coating and further oxygen penetration. The nature of the oxide layer formed on surfaces was dependent upon the temperature & duration of oxidation, the oxygen partial pressure, and moisture content in the circulated air. The oxide layers were consist of mainly of

Table 4. XRD phase pattern as obtained for 2D-C/C –$SiC\text{-} B_4C$ before oxidation.

Ref. code	Score	Compound	Scale factor	Chemical formula	SemiQuant [%]
74-2307	59	Moissanite	0.918	$Si C$	35
83-0861	11	Boron Carbide	0.064	$B_{12} (B C_2)_{0.83} (B_3)_{0.17}$	22
41-1309	9	Boron Silicon	0.089	$B_{305.51} Si_{8.44}$	40
75-0415	12	Silicon Boron	0.069	$Si B_4$	3

Table 5. XRD phase pattern as obtained for 2D- C/C –SiC- B_4C after oxidation.

Ref. code	Score	Compound	Scale factor	Chemical formula	SemiQuant [%]
73-1665	50	Moissanite	0.480	$Si\,C$	10
82-0512	29	Cristobalite	0.435	$Si\,O_2$	6
85-2267	18	Silicon Boron Oxide	0.301	$Si_{30.72}\,B_{1.28}\,O_{64}$	7
86-1122	9	Boron Carbide	0.151	$B_{12}\,(B\,C_2)_{.815}\,(B_3)_{.185}$	29
41-1309	6	Boron Silicon	0.185	$B_{305.51}\,Si_{8.44}$	47

Mo-O, B_2O_3, SiO_2 ; rich in B_2O_3 at low temperatures and rich in SiO_2 at high temperatures. The rapid oxygen transport rates, disruptive phase transformation and brittle characteristics were observed in $MoSi_2$-Al_2O_3 coated samples.

Nearly 250 % of volume expansion were incurred during the oxidation of $MoSi_2$ (assuming complete conversion into SiO_2 and MoO_3[22-23]. This substantial volume expansion produced local wedging stresses at defects viz., inherent micro cracks, pores, and grain boundaries. The stresses also nucleated further cracks and increased the crack formation tendency while exposed to continued oxidation environment. And thus, this was the reason for decrease in oxidation performance of SiC-$MoSi_2$-2% Al_2O_3 in comparison to SiC-B_4C coating. Oxidation of B_4C produces B_2O_3. This B_2O_3 volatiles very fast after 650 °C. That means boron carbide (B_4C) presence would have decreased the oxidation protection beyond 650 °C. However SiC-B_4C coating on 2D C/C exhibited better oxidation resistance and prevented structural collapses. This was due to formation of stable borosilicate layer on the composite by a secondary interaction of B_2O_3 and SiO_2 generated from B_4C , $B_{305.51}\,Si_{8.44}$ and SiC Fig. 5(b), Table 4-5. As show in the Eqn. 1, the liquid B_2O_3-SiO_2 started penetrating into the inherent defect sites and solidified in the sites. The XRD analysis (Table 5) confirms and quantify the presence of the solidified B_2O_3-SiO_2 as $Si_{30.72}\,B_{1.28}\,O_{64}$.

$$B_2O_3\,(l) + SiO_2\,(s) \rightarrow B_2O_3\text{-}\,SiO_2\,(l) \qquad (1)$$

This strengthened the composite and prevented oxygen to diffuse further. There was an increased strength (hardness value rose to an average of 1200Hv1) and improvement on surface appearance of SiC-B_4C coated composite even after 2 to 4 hours of exposure at 1200 °C [Fig. 5 (c)]. With further thermal cycling (cooling to room temperature and re-heating for 1200 °C), there was no major change in weight of the coated composite. The effectiveness of SiC-B_4C coating has also been supported by the research report of Paul experimented on SiC base materials containing elemental ‘boron and carbon” which exhibited increased strength beyond 450 hour heat exposure[24].

Figure 6. 2D C/C brake disc sector with SiC-B_4C coating on non friction sides.

4. CONCLUSION

The as-prepared 2D C/C composites suffer from aggressive oxidation attack at 600 °C and their structure collapsing near 900 °C. The key to raise their potential for brake disc was to improve performance of the composites by appropriate coating and thus coating functionality. In this work, the oxidation behavior of the modified composites were studied in the temperature range of 25 °C -1200 °C in both static and dynamic conditions. It was observed that the sample weight increased slightly for a short initial duration (2-3 minutes) and after that it started decreasing with increasing oxidation temperature and prolonging holding time. Varying oxidation regimes were observed for each coating. The high temperature oxidation results for as discussed coatings have been illustrated in the Table 6.

Table 6. Summarized weight loss results for 2D composites in dynamic and isothermal oxidation testing up to 1200 °C.

S. No	Coatings applied	Wt loss % 2D
1	C-C-SiC	32.5
2	C-C-SiC-$MoSi_2$-Al_2O_3	38
3	C- C-SiC-B_4C	30

Among all the multilayer protection as studied, SiC-B_4C layer was observed to be effective and it performs well for 2D C/C for more than 2 hours of 1200 °C exposure and further thermal cycling. As a flash temperature of 1000 °C-1150 °C develops for maximum 30 seconds during a high speed braking, it is inferred that the above rigid tests show ‘2D C-C-SiC-B_4C’ system is effective in improving the efficiency of carbon-carbon brakes for high speed braking applications. Figure 6 presents 2D C/C brake discs with SiC-B_4C coatings applied on non friction sides and are being studied for further commercial use.

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