Tribological Analysis on Basalt/Aramid Hybrid Fiber Reinforced Polyimide Composites: An Alternate Brake Pad Material

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Keywords:

Polyimide
Basalt fiber
Aramid fiber
Pin-on-disc
Wear rate
Coefficient of friction

ABSTRACT

Fiber reinforcement in polymer matrix contribute significant role in improving mechanical and tribological behavior of any composite for friction application. Hence such composites are developed by selecting suitable matrix and reinforcement materials. In the present study three frictional composite materials were prepared by varying basalt fiber, aramid fiber and hybrid of both theses fibers. Namely Basalt Fiber reinforced composite (BFRC), Aramid Fiber reinforced composite (AFRC) and Hybrid of these fibers reinforced Composite (HFRC), with polyimide matrix. The other ingredients were mixed in constant proportions to enhance the frictional property of the composites and specimens were prepared using hot compression molding machine. The pin-on-disc testing was carried out with different loading condition of 20, 30 and 40 N and varying sliding velocities of 150, 200 and 250 rpm to understand the effect of these parameters on coefficient of friction and the wear rate of specimens. Based on results, contour were developed using Minitab software. HFRC shows the best tribological characteristics compared to BFRC and AFRC. The contact temperature is less for HFRC due to the good heat conduction by hybrid fibers. The thermal stability and the degradation of composites were study from Differential scanning calorimetry (DSC) and Thermogravimetric Analysis (TGA) respectively. It is observed that HFRC has better thermal stability. The Scanning Electron Microscopy images shows better bonding of matrix and fiber for HFRC compared to other composites and various mechanisms were identified along the wear regime areas.

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Received: 22 June 2020

Revised: 28 April 2020

Accepted: 2 December 2020

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1. INTRODUCTION

Brakes are essential parts of any system that is in motion, which is responsible for the safety of

the machine as well as the human beings, by gradually slowing down and stopping the moving parts. It is an abrasive device that converts the kinetic energy of the rotating

system in to heat energy that is lead into the atmosphere. Various kinds of brake pad materials mostly employed in automotive are semi-metallic brake pads, non-asbestos organic (NAO) and low-metallic, NAO and ceramic based brake pads [1]. The quality of disc brake materials is highly depends upon the mechanical and thermal behaviour of the materials used [2].

Due to the health issues caused by asbestos, fiber reinforced NAO composites are mostly used in brake materials in automotives. Polymer composites have been gaining a lot of attention in recent years owing to their ease in processing at the same time offering excellent wear resistance [3,4]. Several hundred ingredients have been amalgamated with the brake pad composites to attain the needed quality [6,7]. These Ingredients are classified as binders, friction generators, and fibers [8,9].

The binders are used to provide the structural reinforcement and effective adhesion to hold rest of the ingredients together. Polyimide (PI) has gained lot of attraction as a recent binder, due to their following proprieties such as excellent mechanical properties, low wear rate, high thermal with stand ability, high constancy in vacuum, low radiation and non-soluble [10-12]. Excellent sliding property can be achieved by combination of proper fiber and solid lubricant [13].

Fibers are mainly used for reinforcement and to enhance the thermal stability of the composites. Basalt fiber is popularly known for its anti-corrosion ability, fire resistant by nature and good resistance to abrasion. Its strength is also higher than both fiberglass and carbon fiber [14]. Researchers have demonstrated and proved that incision of such fibers as reinforcement has enhanced the wear resistance, increase the coefficient of friction as well as thermal stability [5]. Basalt fiber reinforced Polyimide composites displayed an improved wear resistance compared to Poly vinyl product [10]. Aramid fiber is one of the commonly used fibers as reinforcement that decreases the wear rate, due to its physical properties like fibrillation, elongation, ductility and thermal stability [12,14]. The hybrid reinforcement of basalt sand aramid fiber in binder material enhances the strength,

thermal stability and wear resistance of the composite [15-18].

Abrasives materials are widely used to reduce the wear rate and enhance frictional coefficient. Filler are generally used to fill up the space and to give stability at elevated temperatures, materials used as fillers may be either organic such as sawdust, coconut, walnut and cashew nut shell powder [19,20] etc., or inorganic such as barium sulphate, calcium carbonate, vermiculate etc. that decreases wear. The other filler materials such as iron powder, copper powder and aluminium are used to increase friction in the composites. Lubricant reduces direct contact of the interacting frictional surfaces by preventing micro sticks to the rotor effectively decreasing the wear rate, graphite, molybdenum disulphide are some widely used lubricants [21,22].

Various research studies carried out have identified that during the breaking operation the major possible failures are chemical modification, thermal instability, high wear rate and propagation of Cracks [23]. Other investigations conducted have also revealed the different means by which wear can take place in polymer composites are by fiber damage, fiber-binder agglomeration, and matrix crack [24-26]. Some additional but vital means of wear are pull-out of fiber, matrix wear caused by fibre movement, matrix peel-off, twist of the fibers due to shear, and wear track edge bend [27-29].

When a brake is applied the temperature at the contact area of a frictional material increases, which causes failure of brake pad [30]. A frictional material should be thermally stable, when the contact temperature increases beyond 600 oC normally [31]. At any temperature below 800 oC the brake pad material should not have any chemical changes and eventually should not decompose. In many existing frictional materials the chemical structure changes [32].

Therefore, in the present work new frictional composite materials was developed by blending and compacting polyimide matrix with basalt and aramid fibers as reinforcement along with appropriate fillers to enhance the frictional properties. Wear resistance and coefficient of friction was checked by performing pin-on-disc test and the tribological characteristic of the friction composite was examined.

2. MATERIALS AND METHODS

2.1 Materials and ingredients

The basic raw materials selected for the development of the frictional material are thermoset polymer binder and high strength fibers. Polyimide powder used as the binder (PI) in this work was obtained from ABR ORGANICS LIMITED (Andhra Pradesh, INDIA). The polyimide powder and physical properties are shown in Fig. 1a and Table 1a respectively.

Fig. 1. (a) Polyimide Powder, (b) Aramid Fiber, (c) Basalt Fiber.

Table 1a. Physical properties of polyimide.

Chemical	%
Silicon dioxide	52.8
Aluminium oxide	17.5
Iron (III) oxide	10.3
Magnesium oxide	4.63
Calcium oxide	8.59
Sodium oxide	3.34
Potassium oxide	1.46
Titanium dioxide	4.38
Phosphorus pentoxide	0.28
Manganese oxide	0.16
Chromium(III) oxide	0.06

Table 1b. Chemical composition of Basalt fiber [33].

Appearance	Pale Yellow
Bulk Density	0.8 gm/cc
Melting Temperature	110 oC
Viscosity	0.06 dl/gm
Solubility	MF Solution
Curing Temperature	180-220 oC

Aramid fiber was obtained from Go Green Products, Chennai, India. Aramid has a tensile strength of 2700 MPa and Young's modulus of 70.5 GPa. The Figure 1b shows the schematic sketch of aramid fiber. Saline treated chopped basalt fiber was purchased from muthagiri Industries PVT LTD, Mumbai, India. Basalt fiber has tensile strength of 3500 MPa, elastic modulus of 95 GPa and elongation at break of

2.4 %. The Figure 1c and Table 1b represents the sketch and chemical composition of basalt fiber respectively. The other filler ingredients as indicated in Table 2 were procured from Lab chemicals, Chennai, India.

Table 2. Ingredients for the compaction of three different brake pad composites.

Ingredients	Weight fraction for basalt fiber reinforced composite (BFRC)	Weight fraction for Aramid fiber reinforced composite (AFRC)	Weight fraction for Hybrid fiber reinforced composite (HFRC)
Polyimide	31	31	31
Aramid	6	-	3
Basalt	-	6	3
Barite	10	10	10
Potassium titanate	6	6	6
Vermiculite	7.5	7.5	7.5
Molybdenum disulfide	1.3	1.3	1.3
Aluminum oxide	7	7	7
Graphite	11.2	11.2	11.2
Coke	15	15	15
Magnesium oxide	5	5	5

2.2 Treatment of aramid fiber

Aramid fiber was soaked in 10 % sodium hydroxide for 1hour and then washed with distilled water 4 to 5 times so that the PH value reaches 7. The fiber was dried in hot air oven for 5 hrs, maintaining 80 oC to remove the moisture. Polyimide (PI) powder is dissolved in DMF (Dimethyl foramide) solution by adding pinch by pinch until all the powder clearly dissolve in DMF and the color of the solution turns pale yellow. The dried aramid fiber is soaked in this DMF/PI mixed solution and left in it for 30 minutes. Finally the fiber was dried for 5 hrs at 80 oC in oven [23].

The surface treatment is basically to carry out in order to have better adhesive bonding and improve interfacial bonding between the matrix and other ingredients and with the fibers [34]. The saline treatment in basalt fiber will increase the roughness and shear strength. The surface treatment of aramid fiber by coating PI matrix with coupling agent DMF will increase the surface roughness and interfacial shear stress

[35]. Hence the treatment of fibers will increase the bonding nature of the composites.

2.3 Preparation of the composite

Frictional composites of three varying composition were made using polyimide powder reinforced with basalt, aramid and there hybrid. Table 2 shows the other ingredients namely abrasives, fillers, friction modifiers and solid lubricants used for the preparation of the composite. The constituents were thoroughly mixed using a low speed stirrer for around 1 min to get a homogeneous mixer. The die, with 12 cylindrical cavity of dimension (dia. = 10 mm and length = 30 mm) was pre heated to 180 oC inside compression molding machine. The die was removed and mixed powder was then poured into it, rammed and closed. The mold was put back into the compression molding machine again, gradually applying the load till the mixture is completely compressed and the temperature of 180 oC for a period of 1 hour was maintained. The maximum load applied is 20 MPa for about 1 hour. The mold was removed and settles to cool down to atmospheric temperature then the specimens were removed from the die. Figure 2 represents the specimens obtained by hot compression molding.

Fig. 2. (a) BFRC specimen, (b) AFRC specimen, (c) HFRC specimen.

2.4 Post curing of specimens

Post curing of the composite (in air) at 200 oC for 5 hours; This done by gradually increasing the temperature, like 50 oC and maintain it for 1 hour, then increase the temperature to 100 oC and maintain it for one more hour. Further the temperature is raised to 150 oC and allows it under the same condition for 30 minutes and after that the temperature is increased to 200 oC and maintained for 2 hours continuously. Finally the oven is switched off and allowed to cool gradually without taking the specimen out of the oven for 10 hours. This is done to reduce the heat of the composites gradually.

2.5 SEM analysis

Scanning Electron Microscope (SEM) image of the three frictional composite was taken for the purpose of examining the morphological structure of the composites and to understand the positions of the ingredients and fibers in the binders. The FE-SEM images were observed in FEI Quanta 200F instrument available at NCR, SRMIST, Chennai, India.

2.6 Rockwell hardness test

Hardness of the composites was tested in Rockwell Hardness testing machine at 100 kgf and 12.70 mm ball indenter S Scale (SRMIST, KTR). The hardness values of the composites were checked to identify the disc material to be used in pin-on-disc apparatus. It is clear that the hardness of the disc should be maximum, when compared to material that slights on it to understand the wear properties of the materials.

2.7 Wear test

Frictional and wear behavior for dry sliding condition of the composites were made according to ASTM G99 test standard and examined using Pin-on-disc tester. The test were conducted at Normal Load and sliding velocity of 20, 30 and 40 N; and 150, 200, 250 rpm for a period of 20 min respectively. The test reveals the values of coefficient of friction and wear loss along with loss of weight of the specimens. Around five specimens in each trial were tested and average value was recorded with standard deviation. The Figure 3 shows the pin-on-disc setup used in this testing process.

Fig. 3. Pin on disc tester.

Generally the weight loss of the specimen occurs in the form of material removal subjected to friction contact, weight before and after the test is measured used gram weighing machine. The

contact temperature was measured using a thermocouple inserted in the holes provided in the specimens. The Wear Loss is the thickness of pin layer removed after friction in the pin-on-disc tester.

$$\text{Wear Loss } (\mu\text{m}) = L_b - L_a \quad (1)$$

Where, L_b – Length of pin before friction action
 L_a – Length of pin after friction action.

2.8 Thermal test

The samples are tested for analyzing the thermal behaviour in DSC 200F3 Maia Machine at Netzsch laboratories, Chennai. The temperature of observation is from 30 to 500 oC by heating at the rate of 10 K/min under nitrogen atmosphere. The degradation properties of the samples are tested by TGA, carried out at CIPET, Chennai. Samples are tested at temperature between 50 and 900 oC at the heating rate of 20 oC/min.

3. RESULTS AND DISCUSSION

3.1 Selection of disc material based on hardness

Table 3 shows the hardness of the composites used for study. BFRC composite shows higher hardness of 50 when compared to AFRC and HFRC. As the hardness of the material composites is in between 40–55 HRS, EN31 disc material is chosen for the wear test.

Table 3. Hardness of the Sample in HRS.

Samples	Trial 1	Trial 2	Trial 3	Trial 4	Average
BFRC	50.5	55	56.6	58.5	55 ± 0.20
AFRC	38.8	40.5	42.7	41.9	41 ± 0.10
HFRC	48.5	51.8	52.6	53.5	51 ± 0.40

3.2 Tribological characterization of BFRC

Figure 4a shows the SEM image of BFRC, that shows the basalt fiber are randomly oriented, deeply rooted and has fused well with the PI matrix and other ingredients. This in turn increases the tenacity as well as improves the hardness of the composite [36]. From Figs. 4b and 4c it is clear that frictional coefficient decrease as the load increases and it increases as the sliding velocity increases under specific loading condition.

(a)

(b)

(c)

(d)

Fig. 4. (a) SEM Image of BFRC, (b) Coeff. of friction of BFRC, (c) wear loss of BFRC and (d) Contour plot of BFRC.

Table 4. Wear Loss and COF of BFRC specimens.

Normal Load (N)	Sliding Velocity (rpm)	Wear Loss (microns)	Frictional coefficient (μ)	Contact Temperature ($^{\circ}\text{C}$)
20	150	1.2641	0.224	112
30	150	1.5324	0.216	114
40	150	1.8280	0.210	115
20	200	1.2896	0.251	119
30	200	1.6318	0.244	121
40	200	1.4210	0.237	122
20	250	1.3577	0.271	123
30	250	1.7321	0.256	125
40	250	1.8487	0.241	126

This may be due to development of friction layer, which is harder at lower load and as load increases the asperities at the interfaces gets deformed and breaks, results in the formation of loose granular layer and increases the contact area, this leads to the increase of frictional coefficient [37]. Table 4 represents the wear test results obtained for BFRC. The wear rate is found to increase at low and high velocity, this may occur due to the raise in temperature. This results in strength reduction due to fiber-matrix bonding weakness that leads to continuous wear loss [38,39]. It can be observed that at higher speed and with increase in load there is a small decline in wear may be because of greater adhesion particles with the pad surface. When load is increased further the tackiness wears-off increasing the wear rate [40].

Figure 4d represents the contour plot of the wear loss of BFRC specimen under normal load and specific sliding velocity. It can be inferred that 60 % of the contour area represents mild wear loss (1.0 to 1.5 μm), 30 % area represents sever wear loss (1.5 to 1.75 μm) and finally ultra-sever wear loss is 10 % (more than 1.75 μm).

3.3 Contact temperature of BFRC

The contact temperature of BFRC increases with the increase in wear rate and co-efficient of friction in consistently as shown in Fig. 5.

The wear loss and the co-efficient of friction drops with increase in the temperature may be due to thermal softening of polymer matrix. The relationship of contact temperature and coefficient of friction of brake material is determined by the self lubrication fillers that are used in the composite. When the brake antifriction materials are formed on the surface

and the counter face, the process of this formation is controlled by temperature and the material composition.

Fig. 5. BFRC temperature at contact surface.

3.4 Tribological characteristics of AFRC

Figure 6a represents the SEM image of AFRC, it can be observed that aramid fibres are randomly distributed in the matrix and there is a cluster formation may weak the bonding nature between the matrix and fibres. This may results in the reduction of hardness and compaction strength of the AFRC composites, which ultimately lead to more wear loss in this composites compared to other composites [34]. Voids could also be found in the composite which suggest that the sintering of the ingredients with the polymer matrix has not occurred properly, that leads to weak bonding [34,35]. Table 5 represents the wear test results obtained for AFRC. Figures 6b and 6c shows the coefficient of friction and wear loss appear to increase continuously at low to high sliding velocity with increase in load. This may be due to the reduction of the space between the two sliding surfaces causing more wear debris to be formed between the contact surfaces resulting in increased lubrication [18,20]. The frictional

force between the contact surfaces are less compared to the applied force and hence the coefficient of friction increases and this may be due to the surface treatment of aramid fibers. The increase in load may results in debris formation which gets adhered to the sliding surfaces and piles up to form a much thick layer with a more contact area that serves as lubricant at the sliding interface there by reducing the coefficient of friction [41,42]. This concept may be correlated to the thermal and mechanical property of fiber which protects the polymer matrix from the severe wear at elevated temperature [43-45].

Fig. 6. (a) SEM Image of AFRC, (b) Coeff. of friction of AFRC, (c) wear loss of AFRC and (d) Contour plot of AFRC.

At higher sliding velocities the coefficient of friction has no major variation, at the same time wear loss reduces with raise in load, this might be because of the increase in temperature resulting in adhesion of fiber with the sliding surface making the further material removal difficult there by reducing wear loss to a greater extent [23]. Figure 6d represents the contour plot of wear loss under normal load and sliding velocity of AFRC specimen. It can be inferred that around 40 % of the contour area represents mild wear (wear loss between 0.5 to 1.5 μm), approximately 50 % area represents sever wear region (wear loss between 1.5 to 2.1 μm) and finally approximately 20 % represents area represents ultra-sever wear region (wear loss $>2.1 \mu\text{m}$).

Table 5. Wear Loss and COF of AFRC specimens.

Normal Load (N)	Sliding Velocity (rpm)	Wear Loss (microns)	Frictional coefficient (μ)	Contact Temperature ($^{\circ}\text{C}$)
20	150	0.5307	0.196	116
30	150	1.0084	0.206	116
40	150	2.1019	0.209	118
20	200	0.8908	0.211	120
30	200	1.3524	0.217	121
40	200	2.2431	0.223	124
20	250	1.0361	0.223	127
30	250	1.5324	0.231	128
40	250	2.4320	0.227	130

Table 6. Wear Loss and COF of HFRC specimens.

Normal Load (N)	Sliding Velocity (rpm)	Wear Loss (microns)	Frictional Coefficient (μ)	Contact Temperature ($^{\circ}\text{C}$)
20	150	0.9554	0.196	97
30	150	0.9908	0.209	101
40	150	0.7851	0.203	103
20	200	1.0328	0.211	107
30	200	1.4862	0.226	106
40	200	0.8067	0.223	107
20	250	1.2031	0.232	110
30	250	1.7341	0.246	109
40	250	0.9325	0.249	113

3.5 Contact temperature of AFRC

When AFRC is subjected to wear test the contact temperature increases with the increase in the wear loss and the frictional coefficient is shown in Fig. 7. This may be due to the intermolecular dispersion forces.

Fig. 7. AFRC temperature at contact surface.

The increase in temperature with the variation in the wear loss and coefficient of friction may also be due to the chemical composition and the nature of intermolecular interaction of polyimide binder. However the effect of temperature of the frictional properties of polyimide is characterized by a weak relationship between friction coefficient and temperature.

3.6 Tribological characteristics of HFRC

Figure 8a represents the structural image of HFRC that shows the aramid fiber got well entangled with the basalt fiber strands which increased the strength as well as density of the composite as a whole, better amalgamation of the fibers and other ingredients with the PI matrix could also be witnessed from the image. It is also noticed that sintering of the matrix taken place uniformly and the fibers have gone rooted deeply

into the matrix and has fused well with rest of the ingredients, no voids could be seen as such, which ultimately leads to better wear performance of the composite as it is evident from the Figs. 8b and 8c representing the friction coefficient and wear loss based on normal load [46]. At all the loads and sliding velocities, the coefficient of friction seems to increase initially and then decreases gradually which can be attributed to a steady state period wherein the coefficient of friction becomes stable after the generation and peel off of the transfer film during the initial stage at which coefficient of friction is found to be much higher [47].

(a)

(b)

Fig. 8. (a) SEM Image of HFRC, (b) Coefficient of friction of HFRC, (c) wear rate of HFRC and (d) Contour plot of HFRC.

Table 6 represents the wear test results obtained for HFRC. Where as in case of wear loss at lower speeds the wear loss seems to be medium initially then increases because of initial rubbing of the two sliding surfaces which results in the formation of debris in between the friction surface that relatively increases the wear loss. When the temperature increases with further increase in load, this dense layer gets vanished and adapted to strong abrasives. Due to this the wear loss increases again [39].

The drop in wear loss occurs as the load increases, this may be because of the ironing mechanism caused by friction-induced heat which makes material removal from the pin more difficult [23]. At medium and higher speeds with increasing load, it is found that there is significant drop in wear and is found to be minimal which can be attributed to the mechanical and thermal behavior of the hybrid fiber reinforced composite as well as the exposure of well entangled basalt and aramid

fibers at the sliding interfaces [18,43,45,48]. Figure 8d represents the contour plot of the wear loss based on normal load and corresponding sliding velocity of HFRC specimen. It can be inferred that approximately 76 % of the contour area represents mild wear (wear loss between 0.7 to 1.2 μm), around 6 % area represents sever wear region (wear loss between 1 to 1.6 μm) and finally around 2 % represents area represents ultra-sever wear region (wear loss is more than 1.6 μm).

3.7 Contact temperature of HFRC

The contact temperature varies with respect the wear loss and the frictional co-efficient are unpredictable. It was observed that the hybridization of fiber namely aramid and basalt fibres, which induce synergetic property that enhance the thermal stability of HFRC.

Fig. 9. HFRC temperature at contact surface.

This may be due to the inherent in compatibility that happened between the organic aramid fibre and inorganic basalt fibre. The actual area of contact and the shear strength of polymers in respective temperature ranges also affect the wear loss and coefficient of friction.

3.8 DSC analysis of BFRC, AFRC and HFRC

Figure 10 shows the DSC results of BFRC, AFRC and HFRC frictional composites and the output of the DSC test results obtained for each brake pad specimen is given in Table 7. The curve shows a heat flow as an exothermic process in all sliding condition and applied load. The glass transition temperature of BFRC, AFRC and HFRC are 236.3 °C, 242.36 °C and 246.7 °C respectively. AFRC exhibits low T_g value may be due to the

less T_g value of aramid compared to basalt fibre. Whereas the glass transition temperature of basalt is high and hence the composites BFRC and HFRC have relatively better T_g values.

Fig. 10. DSC curve of the composites.

Table 7. Differential Scanning Calorimetry Results.

Sl. No	Specimen	Glass Transition Temperature		Degradation Temperature	
		Mid (°C)	C_p (J/g *K)	Area (J/g)	Peak (°C)
1	AFRC	236.3	0.043	39.95	342.9
2	BFRC	242.4	0.045	28.46	359.0
3	HFRC	246.7	0.052	57.26	373.8

An exothermic curve creeps after attaining the glass transition temperature by all the samples. In general after reaching a temperature of 300 °C temperature the is an endothermic fall in the DSC curve may be due to degradation of filler and binders. The degradation peaks are observed for BFRC, AFRC and HFRC composites are 342.9, 359 and 373.8 °C respectively. Predominantly above 300 °C, the mass loss condensation stage is involved in formation of Polyimide ring amine group that results in mass loss [49]. From DSC curve we observe HFRC has the highest degradation temperature compared to AFRC and BFRC. Hence HFRC can be rated as best thermal stable material for frictional applications. It is also noted that due to the presents of basalt and aramid in HFRC, good bonding that is shown in the SEM image proves that the heat transfer along the fibres, improves the thermal stability of the composite rather than other composites [50,51].

3.9 TGA analysis of BFRC, AFRC and HFRC

The Figure 11 indicates TGA of HFRC, AFRC and HFRC composites. The TGA measures the mass loss with respect to the increase in temperature.

The Table 8 shows the degradation temperature of the composites. The TGA results provide information on thermal stability, changes in materials composition, kinetic parameters for chemical reactions in the sample, oxidative stability of the material and estimated life time. The weight loss mechanism may be due to materials decomposition, evaporation, reduction and desorption.

Table 8. Thermo Gravimetry Analysis Results.

Sl. No.	Specimen Sample	Onset 2	
		X (°C)	X (°C)
1	AFRC	345.14	694.91
2	BFRC	355.93	743.92
3	HFRC	361.06	812.23

The weight gain in the TGA curve is due to the oxidation and absorption, all these reactions are kinetic processes depends on the state of reaction. The TGA curve exhibits a two stage degradation process, such as characterization and weight loss phases. The polymeric material remains virtually intact in the first phase [49,52]. The first decomposition temperature for AFRC occurs at 345.14 °C, 355.93 °C for BFRC and 361.06 °C for HFRC.

Fig. 11. TGA curve of the composites.

The second phase of decomposition of the matrix materials releases H_2O , CO_2 , NH_3 , etc. The mass at the stage just happens to lose due to the initial stage of polymerisation. HFRC decomposes at higher temperature due to the better heat with standing capacity. It is noted that when basalt contact hold more heat than the aramid fibre but when the aramid the heat transfer rate increases and hence the hybrid fibre composites ate more thermal stable than the individual [53]. The second phase of decomposition occurs after 600 °C temperature.

HFRC hold good till 812.27 °C temperature rise, whereas the decomposition of AFRC and BFRC are 743.92 °C and 694.91 °C respectively. Overall it is observed that HFRC exhibits better thermal stability when compared to AFRC and BFRC composites [54,55].

4. CONCLUSION

Three different brake pad composites with basalt, aramid and there hybrid fibers were reinforced in polyimide binder were prepared, keeping all other ingredients constant and named as BFRC, AFRC and HFRC respectively. The prepared composites were tested for wear in pin-on-disc apparatus using EN31 steel, diameter of 100 mm, and thickness of 60 mm as rotating disc.

- HFRC is found to be a better choices as an alternative for brake pad, since it showed higher wear resistance compared to other two composite used in this study.
- HFRC composite despite having a medium hardness of 42 HRB proved to be effective in respect of wear rate in comparison to BFRC (50 HRB) and AFRC (35.5 HRB).
- From the obtained SEM images of the three different specimens, HFRC was found to have higher fusion of the fibers with PI and other ingredients matrix as compared to BFRC and AFRC.
- The mild wear regime was higher in HFRC as compared to BFRC and AFRC. This was obtained using MINITAB software.
- The temperature at the contact surface is less for HFRC compared to BFRC and AFRC. This indicates less frictional heat and less wear in HFRC [56].
- The DSc result shows maximum glass transition temperature for HFRC. This is due to good bonding between the matrix and the fibers [57].
- TGA analysis reveals that HFRC sample shows single degradation pattern as other composites. HFRC has better thermal stability, since it degrades at high temperature.

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