CHAPTER 8

FADE AND RECOVERY BEHAVIOUR OF
BASALT-RECYCLED ARAMID FIBER REINFORCED
HYBRID FRICITION COMPOSITES

8.1 INTRODUCTION

The fade is a detrimental behaviour which occurs due to thermal degradation of organic polymer matrix, formation of load carrying friction film at the friction interface and loss of mechanical properties of the friction composites (Satapathy and Bijwe 2005a). To control such a harmful effect, the friction composite must comprise of thermosetting resin (phenol formaldehyde resin) matrix along with various fibers and frictional modifiers. The friction composites should possess higher and stable friction coefficient ($\mu$) and lower wear under various operating conditions (Briscoe et al 1998).

8.2 RESULTS AND DISCUSSIONS

From the tribological study of friction composites, the composites C1, C2 and C3 shows better performance towards dry sliding conditions. Hence, it is decided to study the influence of fiber reinforcement and effect of thermal stability on fade-$\mu$ and recovery-$\mu$ behaviour of hybrid friction composites C1, C2 and C3 and is explained in the following sections.

8.2.1 Fade and Recovery Cycles of Hybrid Friction Composites

The fade and recovery response of composites C1, C2 and C3 at a constant speed of 411 rpm, constant interval of 10 s and constant load of
617 N are shown in Figures 8.1 (a-c). It incorporates the performance $\mu$ (average $\mu$ over all the braking), the fade $\mu$, and the recovery $\mu$. This investigation evaluates the fade and recovery behaviour of friction composites by variation in $\mu$ with a rise in disc temperature during fade and recovery stage of friction test. During the friction test, the fade and recovery $\mu$ and disc temperature were recorded continuously. At least 20 data points were recorded at each stage. Figures 8.1(a-c) describes the fade and recovery behaviours of hybrid friction composites as a function of temperature. Fade designates the loss in braking effectiveness of a friction material at elevated temperature, typically in the range of 482 to 752°F. From the Figures 8.1(a-c) it can be observed that the developed composites showed the $\mu$ in the range of 0.26 to 0.55 which is in industrial applications range. Generally the values of friction coefficient ($\mu$) of friction composite are lies between 0.3 and 0.6 (Blau, 2001). The variations of $\mu$ during braking depends on the changes of the real area of contacts at the friction interface, the strength of the phenolic binder resin and the frictional characteristics of the constituents at elevated temperatures.

(a)

**Figure 8.1** Fade and recovery cycles of friction composites (a) C1, (b) C2 and (c) C3 respectively
Figure 8.1 (Continued)
While braking, the temperature rise will be between 50-350°C and this temperature zone is very crucial to determine the fade characteristics of friction composites. In the first fade cycle, the magnitude of $\mu$ for composite C1 increases slightly with an increase in temperature up to 200°C and then decreases and reaches near the initial position of the test. The increase in $\mu$ with increasing temperature is mainly due to the formation of primary plateaus. The primary plateaus are formed by broken fibers and other hard inclusions which are embedded on the surface of the composites. However, the composites C2 and C3 follow the trend of decrease in $\mu$ with an increase in drum temperature and are subject to more frictional undulations. On the other hand, during the second fade cycle, the overall magnitude of $\mu$ dropped down prominently around 300°C and remained constant until 350°C. This is due to at high temperature; the low molecular weight of phenol formaldehyde resin in the friction composites causes them to burn off rapidly. Hence, phenol formaldehyde resin starts to melt and act as a lubricant between the friction composite and rotor drum and causes the brake to slip. Also, the amount of glazed layer of the phenol formaldehyde resin present on the surface leads to reduction in the restoration of the friction coefficient. The decrease in $\mu$ was attributed to the increase in sliding temperature between friction composite and brake drum. On the contrary, during recovery test the $\mu$ of all composite C1 increases with decrease in temperature and quickly recovered to its original magnitude. However, the recovery behaviour of composite C2 and C3 is very poor due to its lower thermal stability behaviour. The revival of $\mu$ during the recovery cycle depends on the formation of types of friction film (plateaus) on the surface after the completion of the fade cycle.

From the Figures 8.1 (a-c), it can be confirmed that, during the fade test, the friction coefficient of composites C1, C2 and C3 decreases with an increase in drum temperature, whereas in the recovery test, the $\mu$ of composites increases with decrease in temperature. The variation in $\mu$
increases with an increase in drum temperature for all specimens shown in Figures 8.1 (a-c). This is due to, during braking the frictional heat is generated at the friction interface of the composites and then the interface surfaces and the disc are allowed to cool down on release of brake which causes shear-induced thermo-mechanical stressed state in the friction composites and relaxation of friction surface. The frictional surface relaxation thus developed reduces the deformation of heterogeneous friction film of the friction composites. This reduction in friction film deformability imparts brittleness in the friction films, which easily ruptures or disintegrates the heterogeneous the friction layer. Further, the disintegration of the heterogeneous friction film forms the wear debris at the friction interface by the interfacial compositional domain incompatibility, thermal crazes and also generates a new surface before it is subject to further braking cycle (Satapathy and Bijwe 2005a). Therefore, the degree of recovery behaviour of composites is enhanced when the wear debris particles harder or the adhesive debris particles are higher. But, however, these wear debris gets entrapped between the friction surfaces and forms the third bodies resulting in three-body abrasion (TBA) in the friction composites. Hence, the fade behaviour of composites C2 and C3 are boosted and reduces the frictional performance of the friction composites when compared to composite C1.

The initial friction coefficient instability from the baseline plots is not unusual and normally disappears after a certain number of brake applications in the real braking situation. During second fade test, the $\mu$ of the composites goes to lowest level of 0.26 around 300°C in composite C3. The $\mu$ of composite C3 was found to drop go low that is not even near to the mediocre behaviour which is attributed to the poor thermal stability and higher amount of weight loss (40.43 %) of the composite C3, as confirmed in Figure 5.6 (c) from Chapter 5. From the TG/DTG studies, it can be seen that poor thermal stability and maximum weight loss of friction composites are
due to decreased amount of basalt fiber in the formulation C3. The higher percentage of fibers in the composite C1 causes better thermal stability at elevated temperatures. Hence, lesser weight loss is attributed in composite C1 when compared to other formulations. To understand the synchronous effect of basalt fiber, the thermal stability of fiber from TG/DTG study (Chapter 5) is shown in Figure 5.5. Also, the thermal mobility of the low molecular weight is higher, resulting in the easier plastic deformation, leading to a larger contact area. Hence, the friction value of composite C1 increases when compared to C2 and C3. The fade behaviour at elevated temperatures is related to the thermal decomposition of ingredients and is followed by a subsequent destruction of contact areas at the sliding interface. So the higher thermal stability lined the way for the higher friction stability in the composite C1. A similar study was carried out by Balaji and Kalaichelvan (2012) in hybrid fiber reinforced composite brake pad and observed that inclusion of fiber in friction composites exhibits better thermal stability and fade resistance and increase the friction performances.

A friction composite with a higher amount of hard basalt fiber content resists fiber matrix debonding and enhances better thermal stability during braking. Fibers like basalt and aramid improves the friction and wear resistances of friction materials considerably (Sinha & Biswas 1995, Öztürk et al 2007). Addition of metallic fillers such as copper and iron particles has a diverse role in altering the frictional behaviour and improves the fade resistance, recovery performances and counterface friendliness of the friction composite (Mukesh Kumar & Bijwe 2010). The friction coefficient of the composites is mostly governed by the ploughing action of the reinforcement fiber present in the composites (Crosa & Baumvol 1993). Thus, the hard basalt fiber enhances the ploughing action of the friction composite on the drum surface. Hence a higher $\mu$ (0.55) was observed in composite C1 when compared to C2 (0.52) and C3 (0.45). Higher amount of hard basalt fiber in
the friction composite generates rough friction surface due to increased number of fibers incorporated, resulting increased number of fibers appear on the friction surface. A lower amount of fiber content in composite C3 causes few fibers to appear on the surface, thus reducing the true contact area of the composite. When the rough surface of composite (C1) is worn, primary plateaus are formed as shown in Figure 8.3 (a), as a result the area of true contact between composite and drum increases. A higher the real contact between the worn surfaces results in increased friction coefficient (Eriksson & Jacobson 2002). The higher magnitude of $\mu$ (0.55) of the composite C1 can be attributed to its unique head-tail nature morphology of basalt fiber, as shown in Figure 3.1(a) in Chapter 3. The heads in basalt fiber, often termed as ‘shots’, contain higher degree of hardness. Hence, during braking, the shots act as hard abrasive particles in the composites. These hard particles increase the true contact between friction couple and lead to two-body abrasive wear grooving mechanism in the friction composites (Satapathy and Bijwe 2005a). This has turned into successfully imparting the higher $\mu$ in composite C1 when compared to other formulations.

In the friction composites, basalt fiber exhibits high potential and receives a lot of attention due to its high temperature and abrasion resistance. Incorporation of soft aramid fiber in the friction formulations also enhances the $\mu$ of the composites by forming the viscous glassy layer on the area of contact of counterpart (Horrocks et al 2001). The soft aramid fiber provides stable and higher friction stability and better thermal stability to the friction surfaces and also boosts frictional performances in the composite C1. Also the reinforcement fibers along with hard abrasives such as Fe, Cu, Al$_2$O$_3$ and SiC in the friction formulations increase the true contact area between the friction surfaces which leads to higher $\mu$ in the composite C1. The molykote in the friction composites smeared from the friction surface during sliding and act as the lubricant and reduces the frictional fluctuations of the composites.
Incorporation of cashew friction dust particles to the friction material offer adequate elasticity resulting in stabilized frictional characteristics. This is because the contact area of friction surfaces increases through the elastic deformation on engaging with counterface of the friction at lower temperatures. Hence, higher $\mu$ is maintained in the case of composite C1 throughout the process when compared to other formulations. The various frictional responses of the friction composites are shown in Table 8.1. Figures 8.1 (a-c), reveals that, composite C1 exhibits lesser weight loss when compared to composites C2 and C3. At high temperatures, the organic constituents in the friction composites release gas as a result of thermal degradation or pyrolysis. This gas may be trapped between the sliding interface and an opposing force to the applied load results in reducing the frictional force. Therefore, the fade behaviour of friction composites at elevated temperature is due to the thermal decomposition of ingredients and is followed by a consequent damage of contact areas at the sliding interface. Also, high strength and high modulus fibers in the composites resists thermal degradation by absorbing the major share of stress and dissipates a lower amount of energy as a friction output. It has been reported that the fade behaviour of the friction material could be dominated by a decrease in mechanical strength, thermal degradation of the organic matrix and the formation of load-carrying friction film causing an effective increase in the real contact area and consequently reducing in applied pressure on the friction material composites (Herring 1967 and Wirth et al 1994).

During the friction tests, the coefficient of friction and the drum temperature were recorded continuously. At least 20 data points were recorded for each stage. Two types of friction values i.e., normal friction coefficient (average of four points in the second fade curve located at 93, 121, 149 and 205°C) and hot friction coefficient (average of 10 points located at 206 and 149°C on the first recovery; 233, 261, 127.2, 142.8, 158.3 and
173.9° C on the second fade 260.7, 205 and 149° C on the second recovery) is calculated. The % of first fade-\( \mu \), first recovery-\( \mu \), second fade-\( \mu \) and second recovery-\( \mu \) are calculated which are defined as follows.

<table>
<thead>
<tr>
<th>Performance attributes</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Friction or Fade ( \mu )</td>
<td>0.51</td>
<td>0.50</td>
<td>0.48</td>
</tr>
<tr>
<td>Normal or Recovery ( \mu )</td>
<td>0.55</td>
<td>0.52</td>
<td>0.44</td>
</tr>
<tr>
<td>First fade ( \mu ) (%) (^a)</td>
<td>10.42</td>
<td>15.91</td>
<td>28.21</td>
</tr>
<tr>
<td>First recovery ( \mu ) (%) (^b)</td>
<td>116.67</td>
<td>105.13</td>
<td>93.94</td>
</tr>
<tr>
<td>Second fade ( \mu ) (%) (^c)</td>
<td>7.55</td>
<td>10.42</td>
<td>20.93</td>
</tr>
<tr>
<td>Second recovery ( \mu ) (%) (^d)</td>
<td>96.00</td>
<td>102.17</td>
<td>89.19</td>
</tr>
<tr>
<td>Wear loss (%)</td>
<td>8.08</td>
<td>8.78</td>
<td>8.95</td>
</tr>
</tbody>
</table>

**Calculations**

\(^a\) First Fade \( \mu \) (%) = \{(Initial \( \mu \) – Final \( \mu \))/initial \( \mu \)\} \times 100 (During first fade cycle)

\(^b\) First Recovery \( \mu \) (%) = \{Final \( \mu \)/Initial \( \mu \)\} \times 100 (During first recovery cycle)

\(^c\) Second Fade \( \mu \) (%) = \{(Initial \( \mu \) – Final \( \mu \))/initial \( \mu \)\} \times 100 (During second fade cycle)

\(^d\) Second Recovery \( \mu \) (%) = \{Final \( \mu \)/Initial \( \mu \)\} \times 100 (During second recovery cycle)

\( \mu_{\text{max}} \) = The highest coefficient of friction during fade and recovery test

\( \mu_{\text{min}} \) = The lowest coefficient of friction during fade and recovery test
Magnitude of fade $\mu$ and % of fade for all the composites was in the following order (Table 9.1)

Fade $\mu$: C1 (0.51) $>$ C2 (0.50) $>$ C3 (0.48)

First fade $\mu$ (%): C1 (10.42) $<$ C2 (15.91) $<$ C3 (28.21)

Second fade $\mu$ (%): C1 (7.55) $<$ C2 (10.42) $<$ C3 (20.93)

Magnitude of fade $\mu$ and % of recovery for all the composites was in the following order (Table 9.1)

Recovery $\mu$: C1 (0.55) $>$ C2 (0.52) $>$ C3 (0.44)

First recovery $\mu$ (%): C1 (116.67) $>$ C2 (105.13) $>$ C3 (93.94)

Second recovery $\mu$ (%): C1 (96.00) $<$ C2 (102.17) $>$ C3 (89.19)

The higher damage of friction surface in composite C3 could be due to interfacial thermo chemical changes of the friction composite during braking. At elevated temperatures, the surface energy at the friction surfaces is reduced and generates a related temperate friction surfaces between friction composite and counterface drum resulting in decreased adhesive-cohesive forces between the interfacial friction zones (Williams 1994). This causes the mating surfaces of the friction couple to slip each other without difficulty and resembles the thermo dynamical resemblance nature of the friction film. This friction film imparts the related rheological responses to counter the thermoelastic instability (TEI) at the friction interface and deforms the contact zone while braking (Lee & Barber 1993, Dow 1980). Hence, the $\mu$ of the friction composite C3 was lower and this contributes to the fade behaviour when compared to composite C2 and C3.
8.2.2 Wear behaviour of Friction Composites and Brake Drum

Generally, the harder samples are supposed to have a lower average thickness loss (lower wear). The tribological behaviours are basically evaluated by the nature of interactions between the two friction surface are in contact. The nature and level of interactions between the two surfaces are dependent on the properties of the surfaces and ingredients of composites (Crosa & Baumvol 1993). In the friction material composites, the phenol formaldehyde resin, fibers, and other organic friction modifiers play crucial roles in the wear of the friction materials which occurs due to transformation of temperature of these ingredients (Shin et al. 2010). In general, softening and charring of phenol formaldehyde matrix increases with an increase in drum temperature are a usual phenomenon and this temperature rise causes fiber-matrix debonding at the fiber-matrix interface resulting in detachment of the polymer matrix, and cracking of the deteriorated surface layer (Tanaka et al 1973). Thus, the composite C1 has higher strength due to better fiber-matrix bonding and also tends to exhibits better resistance to wear. Also, hard asperities present on the drum surface determine the wear rate of the friction materials. During automotive braking, abrasive wear is caused at the friction interface by hard particles (wear debris) present in the brake friction lining. These hard asperities act as abrasive particles at the friction interfaces resulting in two-body or three-body abrasion in the friction composites. Sometimes the wear debris particles get entrapped between the friction surfaces, resulting into three-body abrasive wear. Three-body abrasive wear behaviour of hybrid friction composites were clearly discussed in Chapter 6 in order to identify the abrasive wear behaviour of composites C1, C2 and C3 and the conclusions were made in a lined way.

Basalt fiber exhibits high hardness, excellent fiber/matrix adhesion and abrasion resistance to friction materials. Aramid fiber is soft and
improves the wear resistance of composites due to its higher strength and characteristic properties of fibrillation and elongation. Due to the fibrillation nature, it absorbs a higher amount of stress and reduces the residual stress acting in the interface for the abrasive wear (Satapathy and Bijwe 2002). In the hybrid friction composite, the addition of basalt fiber (20 wt %) in composite C1 exhibits a lower wear rate when compared to all other composites. The composite with 25 wt % of fiber (C1, basalt + recycled aramid) is more resistant to fiber-matrix debonding due to keeping matrix integrity at high temperature. However, composite C3 loses its surface integrity at high temperature due to its fiber-matrix debonding behaviour. At high temperature, the thermal degradation and softening of the phenol formaldehyde resin strongly influences the tribological behaviour of the composite. Removal of the fiber due to thermal degradation is not only cause the higher wear. Also, thermal softening and charring effect of the matrix result in debonding of the fibers and enhancing fiber pull-out from the matrix, resulting in loss of structural integrity. A lesser amount of basalt fiber in the composite C3 result in increased debonding reinforcing fibers and fracture in matrix. These deboned fibers can cause an increase in wear rate of the composites by damaging the counterface film. The thermal softening of the matrix reduces the hardness of the composites and thus increasing wear rate of the composite C3. Hence, a higher wear rate was observed in composite C3. The wear loss of the composite follow the trend of C1 (8.08%) < C2 (8.78%) < C3 (8.95%).

Table 8.2 Wear loss due to weight loss of hybrid friction composites

<table>
<thead>
<tr>
<th>S. No</th>
<th>Composite</th>
<th>Weight loss (%) from TGA</th>
<th>Wear loss (%) from chase friction test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>C1</td>
<td>33.32</td>
<td>8.08</td>
</tr>
<tr>
<td>2.</td>
<td>C2</td>
<td>38.57</td>
<td>8.78</td>
</tr>
<tr>
<td>3.</td>
<td>C3</td>
<td>40.43</td>
<td>8.95</td>
</tr>
</tbody>
</table>
8.2.3 Worn Surfaces Morphology of Hybrid Friction Formulations

In the SEM analysis, primary plateaus are denoted by dark coloured patches which in turn have good load carrying capacity, fade resistance ability and reduced wear. The secondary plateaus are denoted by the shiny coloured patches are formed by the back transfer of the organic material such as resin, which is either due to adhesive wear or due to the hot spots formed in the rotor also tends to make it (Choa et al 2005). The load carrying capacity of secondary plateaus is poor due to charred materials, which in turn reduce friction and induce wear. The secondary plateau formation was high in C3 followed by C2 where even more surface cracks are formed, but the C1 showed more primary plateau with less secondary plateau and no surface crack formation. This reduced fade behaviour can be attributed due to its good thermal stability and higher thermal conductivity. The composite C3 was
rougher and covered with secondary plateau supporting the higher extends of third body abrasion in composites which was discussed in Chapter 6. Also, in composite C3, thermal crakes are evident due to its softening and thermal degradation of the matrix, as evident in Figure 8.3 (c). The fiber pull out due to thermal penetration, thermal softening and charring is more in composite C3 when compared to composites C1 and C2. Generation of microcracks in the composite C3 facilitates more wear as compared to other composites. A higher amount of basalt fiber in the composite C1 worked in synergistic manner shows minimal amount of surface damage other than the formation of secondary plateaus. The basalt-recycled aramid fiber combination was antagonistic to the wear debris to the composite C1 while as the surface damage due to broken fibers, hard abrasive debris, secondary plateaus and low-intensity surface cracks are evident in the composite C3.

Figure 8.3  SEM images of friction composite samples (a) C1, (b) C2 and (c) C3 respectively
Figure 8.3 (Continued)
8.3 SUMMARY

Based on the experimental study on fade and recovery of friction composites, the following conclusions can be drawn:

- The experimental tribo-behaviour of the fibers can be efficiently exploited to modify the friction performance of composite such as fade-$\mu$, recovery-$\mu$, and wear within the expected range.

- The basalt–recycled aramid fiber combination in composite C1 (25 wt. %) exhibits a better fade resistance and recovery behaviour when compared to composites C2 and C3. A higher amount of basalt fiber in composite C1 increases friction coefficient and also reduces the wear loss of the composites.

- The composite having higher amount of fiber (basalt + recycled aramid) content (C1, 25 wt %) exhibits lesser weight loss and the higher thermal stability lined the way for the friction stability.

- The composite C1 was found to exhibit more primary plateaus and lesser secondary plateaus and no evident for formation surface cracks. Increased thermal cracks, low-intensity surface cracks, surface damage due to broken fibers, hard abrasive debris, secondary plateaus and fiber pullout were found in composite C3.

- The formation of more primary plateaus which in turn have good load carrying capacity and the secondary plateaus which are formed by the back transfer of the organic material such as resin which is either due to adhesive wear is confirmed by SEM analysis.