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ORIGINAL ARTICLES

Assessment of braking performance of lapinus–wollastonite fibre reinforced friction composite materials

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Abstract Brake friction materials comprising of varying proportions of lapinus and wollastonite fibres are designed, fabricated and characterized for their chemical, physical, mechanical and tribological properties. Tribological performance evaluation in terms of performance coefficient of friction, friction–fade, friction–recovery, disc temperature rise (DTR) and wear is carried out on a Krauss machine following regulations laid down by Economic Commission of Europe (ECE R-90). The increase in wollastonite fibre led to an increase in density and hardness whereas void content, heat swelling, water absorption and compressibility increased with the increased in lapinus fibre. The performance coefficient of friction, friction–fade behaviour and friction–stability have been observed to be highly dependent on the fibre combination ratio i.e. coefficient of friction, fade and friction–stability follow a consistent decrease with a decrease in the lapinus fibre content, whereas the frictional fluctuations in terms of $\mu_{\max} - \mu_{\min}$ have been observed to increase with a decrease in lapinus fibre content. However, with an increase in wollastonite fibre content in formulation mix, a higher wear resistance and recovery response is registered. The worn surface morphology has revealed topographical variations and their underlying role in controlling the friction and wear performance of such brake friction composites.

1. Introduction

Brake friction materials have a crucial role to play in fulfilling the performance requirements such as: high and stable coefficient of friction, low wear along with a low fade and high recovery at wide ranges of operating conditions such as: speed of vehicle, braking temperature, braking force and braking duration for efficient braking of an automotive system.

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Usually, a typical friction material formulation contains many ingredients (sometimes more than 10). The ingredients used can be mainly classified into four prime classes as fibres, space filler, friction modifiers (abrasives, lubricant) and binder (Bijwe, 1997). The role of each class viz. fibres (Satapathy and Bijwe, 2005; Kumar and Bijwe, 2013; Ikpambese et al., 2014), space filler (Handa and Kato, 1996), friction modifier (Cho et al., 2006; Lee et al., 2009) and binder (Bijwe et al., 2005; Shin et al., 2010) in the friction material has been extensively studied for improving the tribological performance and new ingredients are still being developed to attain higher tribo-performance (Dadkar et al., 2009; Singh et al., 2011, 2013a; Yawas et al., 2013; Tiwari et al., 2014; Idris et al., 2015).

Among the many ingredients currently available for friction materials, the fibrous reinforcement: such as organic fibre (Satapathy and Bijwe, 2004), inorganic fibre (Satapathy and Bijwe, 2005; Dadkar et al., 2010), ceramic fibre (Han et al., 2008), metallic fibre (Kumar and Bijwe, 2013) and their combinations (Patnaik et al., 2010; Singh and Patnaik, 2015a) have been found to play a crucial role as they reinforce the composites during fabrication and also help in the formation of topographical features which enhance the tribo-performance. The role of Kevlar fibre has been well reported to aid wear minimization and friction stabilization (Gopal et al., 1996; Kim et al., 2001; Kumar et al., 2011). Lapinus fibres inherently comprising metallic-silicates, when combined synergistically with other fibres that improved the tribo-performance and suppress the unwanted phenomenon like noise, vibration, judder over wide range of driving conditions (Satapathy and Bijwe, 2005; Dadkar et al., 2010; Singh et al., 2015b). Wollastonite fibres having high thermal resilience and inherent hardness have been found to stabilize the coefficient of friction (μ) and maximize recovery performance (Santoso and Anderson, 1985; Kogel et al., 2006).

In the present situation, the development of friction material formulations with stable coefficient of friction, higher recovery performance, higher fade resistance and fibre inclusion is of vital significance. Therefore, the role of lapinus and wollastonite fibres has been reported to improve the recovery, fade, improving wear resistance and stabilizing friction fluctuations over a wide range of braking conditions. Hence, their combination may potentially enhance the tribo-performance for a friction formulation. However, there has been no systematic effort to assess the fade and recovery behaviour as a part of evaluating comprehensive performance of friction formulations containing lapinus and wollastonite fibres in combination. This paper deals with utilization of lapinus and wollastonite fibres in varying proportions to study possible synergistic effect of their combination on the tribological performance parameters such as friction performance, friction fade, recovery and wear characteristics.

2. Experimental procedure

2.1. Materials and fabrication details

Friction material formulation containing by varying the proportion of lapinus (RB-220, Lapinus intelligent fibres, Holland), to Wollastonite fibres (Wolkem India Ltd.) are sheared mixed with fixed amount of phenol–formaldehyde resin of Novolac type (JA-10), barium sulphate, graphite (Graphite India Ltd.) and Kevlar fibre (IF-258, Twaron, Teijin-Germany), that amounting to 100% by weight as depicted in Table 1. The ingredients are mixed sequentially in a plough type shear mixer, where mixing of powdery ingredients is followed by fibrous ingredients to ensure the proper distribution of ingredients before moulding. The mixture is preformed to the shape of brake pads and then heat cured in a compression-moulding machine under a pressure of 15 MPa for 10 min at temperature of 155 °C, with four intermittent breathings to expel volatiles evolved during curing. The specimens are post-cured in an oven at 165 °C for 4 h to relieve residual stresses developed during moulding cycles.

2.2. Physical, chemical and mechanical characterization

The composites are characterized for their physical, chemical and mechanical properties respectively. The density is measured following the standard water displacement method and void content is calculated theoretically by normalization of the actual density with respect to the ideal density. However, the heat swelling is measured according to SAE J160 JNU 80 standard whereas, water absorption is carried out according to ASTM D570-98. Acetone extraction of the cured powdered sample is carried out to estimate the amount of uncured resin present in the friction composite. The mechanical properties such as hardness (a measure of resistance to indentation under loads), cross-breaking/shear strength (a measure of composite adhesion to the back plate) and compressibility characteristics are determined as per standards conforming to industrial practice.

2.3. Tribological performance evaluation methodology

The fade and recovery assessment tests are conducted on a Krauss machine in conformance to regulations laid by Economic commission of Europe (ECE R-90), details of which are mentioned elsewhere (Singh et al., 2013b). The Krauss machine is fully computer-controlled having data acquisition capabilities. Concisely, a pair of friction composites is pressed against the brake disc for undergoing bedding (to ensure conformal contact), cold, fade and recovery cycles.

3. Results and discussion

3.1. Physical, chemical and mechanical properties of the friction composites

The results of physical, chemical and mechanical properties of the friction composites are compiled in Table 2. It can be seen

Table 1 Details of composite composition and designation.

Composition (wt.%)	Composite designation			
	LW-0	LW-1	LW-2	LW-3
Phenol formaldehyde	10	10	10	10
$BaSO_4$	50	50	50	50
Graphite	5	5	5	5
Kevlar fibre	5	5	5	5
Lapinus fibre	30	20	10	0
Wollastonite Fibre	0	10	20	30

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Table 2 Physical, chemical and mechanical properties of the friction composites.

Properties	LW-0	LW-1	LW-2	LW-3
Density (g/cm^3)	2.05	2.08	2.14	2.21
Void content (%)	0.272	0.269	0.256	0.240
Acetone extraction	0.82	0.41	0.48	0.56
Hardness (HRL) ASTM D785	89	92	95	97
Heat swelling	0.32	0.24	0.23	0.18
Compressibility (%)	1.21	1.04	0.98	0.91
Water absorption	0.13	0.09	0.08	0.08
Shear strength (kgf)	1440	1980	1620	1250

from Table 2 that, with an increase in lapinus content followed by complementary decrease in wollastonite content, there is a decrease in density with the increase in void content. This decrease in density may be attributed to the replacement of content of highly dense wollastonite content relatively by less-density lapinus content. Further, the dispersion ability is hampered to a large extent with higher lapinus content leading to an increase in void content. Acetone extraction indicates the amount of uncured resin in the composites, which was negligible in all the composites indicating its apparent non-dependence on the composition. The hardness rises steeply as the wollastonite content increases may be attributed to the fact that wollastonite content results in good mixing and curing of the composites that cause mechanical compaction of the ingredients. Heat swelling, compressibility and water absorption of the investigated friction composites decrease with the increase in wollastonite content. Further, shear strength remains higher for LW-1/LW-2 indicating the role of fibre combination influencing the shear strength showing effective synergism.

3.2. Tribological performance evaluation of the friction composites

The friction response of the investigated composites in terms of variation in coefficient of friction along with corresponding temperature rise of the disc as a function of number of brakings is shown in Fig. 1. The variations of μ_P, μ_F, μ_R and frictional fluctuations ($\mu_{max} - \mu_{min}$) as a function of composition are shown in Fig. 2. The stability and variability aspect of frictional response (stability coefficient and variability coefficient) in relation to composition are shown in Fig. 3. The extent of fade–recovery (%) and the maximum temperature rise of the disc are shown in Fig. 4. The wear as volume losses is shown in Fig. 5 while the surface morphologies of the worn composites as investigated through SEM are shown in Fig. 6.

3.2.1. Friction-evolution as a function of braking cycles

The friction response of the investigated friction composites in terms of variation in coefficient of friction along with corresponding temperature rise of the disc as a function of number of brakings is shown in Fig. 1. From Fig. 1 it is clearly revealed that all the composites demonstrate three distinct stages of friction evolution (friction build-up, friction-peaking and friction-decay stages) irrespective of the composition and the test runs, i.e. cold cycle, fade cycles, and recovery cycle. Fig. 1 shows that all the investigated frictional composites LW-0, LW-1, LW-2 and LW-3 show unsteady friction response in the cold cycle. As seen from Fig. 1a for LW-0, in first fade cycle, μ rose ($\sim$0.5) continuously till third braking and started decreasing sharply till 10th braking. The earlier friction build-up, stable friction-peaking and delayed decay may be attributed to the mild abrasive nature of lapinus fibre that appears to be effective in arresting fading and maintaining higher friction response in LW-0 as found experimentally. As seen from Fig. 1b for LW-1, in first two fade cycles, the behaviour is similar to that of LW-0. However, in further cycles peaks in fade cycles are flatter than those in earlier case indicating lower friction performance of LW-1. In friction composite LW-2 (Fig. 1c) the μ performance remained wildly fluctuating and as a follow-up response abrupt friction peaking accompanied with steep friction-decay within the first 4 braking instances was observed in the first two fade cycles. However, from third fade run onwards the friction response showed signs of stability followed by a nominal trend of friction-decay as compared to earlier fade cycles.

In case of Fig. 1d for LW-3 the general friction response has been fast friction peaking followed by even faster friction decay within first three brakes of first four fade runs. This indicates about the qualitative nature of the composition of the friction film that is operating at the braking interface. The physical characteristics of the accompanying friction layer may be less kinetically controlled and is rather believed to be determined more by the composition. However, in recovery run of all the investigated friction composites (LW-0 to LW-3), the frictional response remained almost identical indicating that the friction stabilization is kinetically controlled till the required phase transformations occurred at the braking interface for the evolution of friction-efficiency. The recovery performance of the investigated composites is observed to be satisfactory in the present study.

3.2.2. Variation of μ-performance (μ_P), μ-fade (μ_F), μ-recovery (μ_R) and friction fluctuations ($\mu_{max} - \mu_{min}$)

The tribological performance parameters such as performance coefficient of friction (μ_p), fade coefficient of friction (μ_F) and recovery coefficient of friction (μ_R) as obtained by tribological performance evaluation in Krauss machine following ECE R-90 norms are depicted in Fig. 2. From Fig. 2 it is apparent that an increase in wollastonite content as compared to lapinus in the formulation results with the decrease of μ_p and μ_F along with an increase in $\mu_{R.}$ This decrease in the μ_p and $\mu_{F,}$ can be attributed to the fact that the incorporation of wollastonite fibres results in the formation of areas of compacted wear debris around the fibres (i.e. load carrying friction films) which aid in friction reduction followed by increased heat dissipation and reduced wear (corroborated by Figs. 4 and 5). However, in case of LW0/LW-1/LW-2, the higher magnitude of friction coefficients may be attributed to the presence of hard lapinus fibre that enhances the abrasive component and aids the thermal resistance of the friction materials contributing to enhanced thermal stabilization (Singh et al., 2014). The increase in μ_R is due to disintegration of loosely compacted wear debris during the recovery cycle leading to the formation of third bodies between the pad and disc interface. These hardened third bodies destroy the friction films formed during cold and fade cycles leading to an increase in friction.

The friction-fluctuations ($\mu_{max} - \mu_{min}$) with composition variables are shown in inset of Fig. 2. The fluctuations remain

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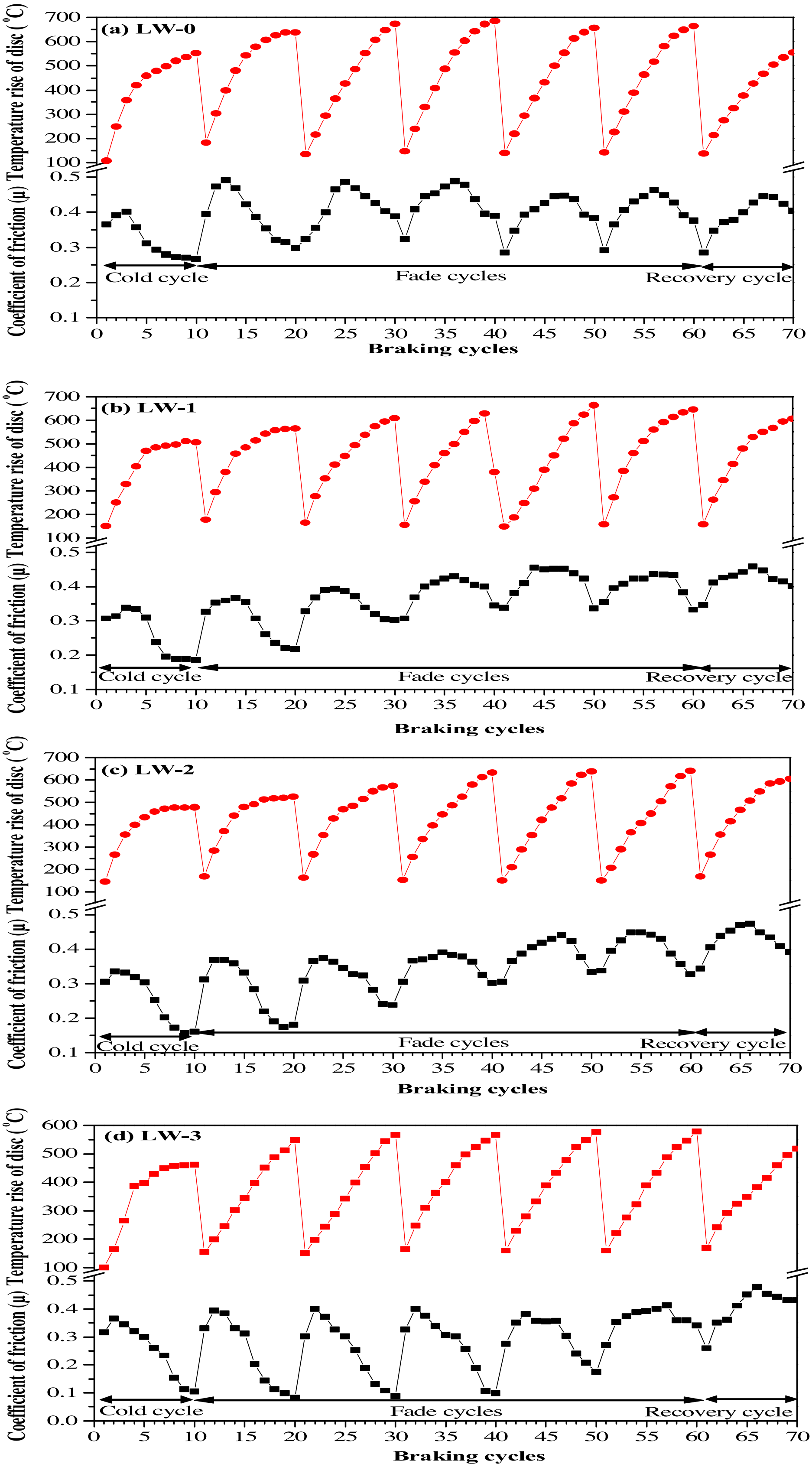

Figure 1 Frictional response of the composites plotted synchronously with the braking induced temperature rise in the disc (a) LW-0 (b) LW-1 (c) LW-2 (d) LW-3.

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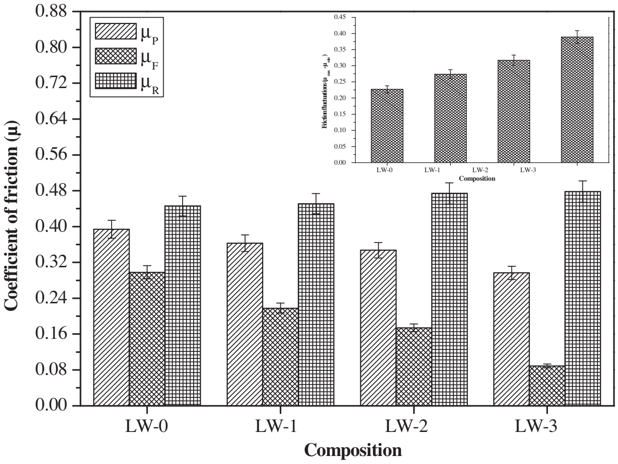

Figure 2 Friction performance of the composites: μ_{P} (μ-performance), μ_{F} (μ-fade) and μ_{R} (μ-recovery) vs. composition. (Inset: frictional fluctuations ($\mu_{\mathrm{max}} - \mu_{\mathrm{min}}$) vs. composition).

high in formulation having 30 wt.% of wollastonite, whereas it remains lower for formulation having lapinus content only i.e. LW-0. Hence, comprehensively, the formulations having a higher response to μ-performance show lower fluctuations in frictional response. Friction composites LW-1/LW-2 are likely to have higher susceptibility to noise, vibration propensity, judder etc. that should be as low as possible. The composition having 30 wt.% of lapinus fibre i.e. LW-0 with least friction fluctuations (0.227) proved effective in the absorption of vibrations generated during the braking operation and minimizing the unwanted phenomenon like judder, noise to a larger extent as compared to other compositions.

3.2.3. Friction stability and variability

The stability and variability aspect of frictional response in terms of stability coefficient and variability coefficient in relation to composition variables is shown in Fig. 3. The stability coefficient is the ratio of μ-performance to μ-maximum whereas, variability coefficient is calculated as the ratio of μ-minimum to μ-maximum (Singh et al., 2013a,b).

It is also observed that LW-0 formulation shows higher stability coefficient as well as variability coefficient, whereas LW-3 formulation shows lowest stability and variability coefficient.

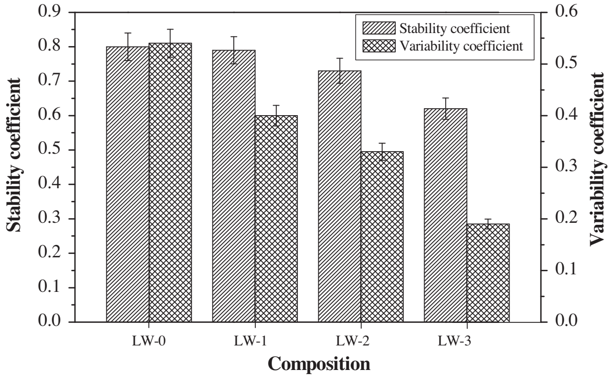

Figure 3 Stability and variability coefficients of the composites vs. composition.

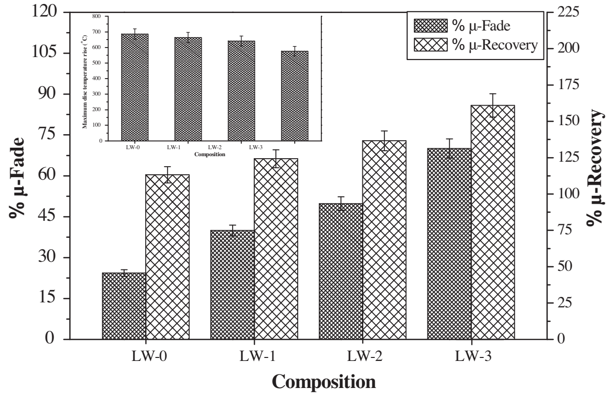

Figure 4 %-Fade and %-recovery performance of the composites vs. composition. Inset: maximum disc temperature rise vs. composition.

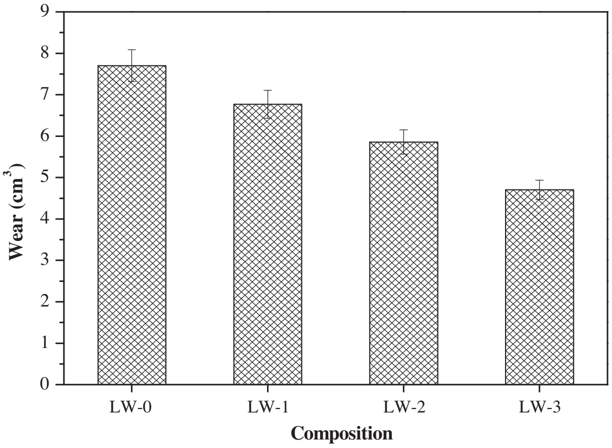

Figure 5 Wear of the composite vs. composition.

It is required that stability coefficient should be as high as possible and variability coefficient should be as low as possible for the efficient frictional response while braking. Thus, formulation of LW-0 having lapinus fibre alone proved effective from stability point of view whereas, LW-3 formulation having only wollastonite fibre shows least variability for efficient braking performance.

3.2.4. Fade–recovery performance and temperature rise of the disc

Fig. 4 shows the plot between percentage fade and percentage recovery for the various compositions studied in this work. It is clearly seen from Fig. 4 that, with an increase in the wollastonite fibre content there is a simultaneous increase in both fade and recovery percentage. This could be explained by the fact that with an increase in the fibre content, on one hand there occurs formation of load carrying friction films by wear debris compaction at higher temperature causing the resin to char and reduce friction, and on the other hand there is disintegration of these films at lower temperature due to poor binding of matrix with surrounding filler/fibres, causing a rise in friction. The inset of Fig. 4 shows maximum disc temperature rise (DTR) as a function of compositions. The trend in disc temperature rise is same as the one for μ_{p}, that shows an

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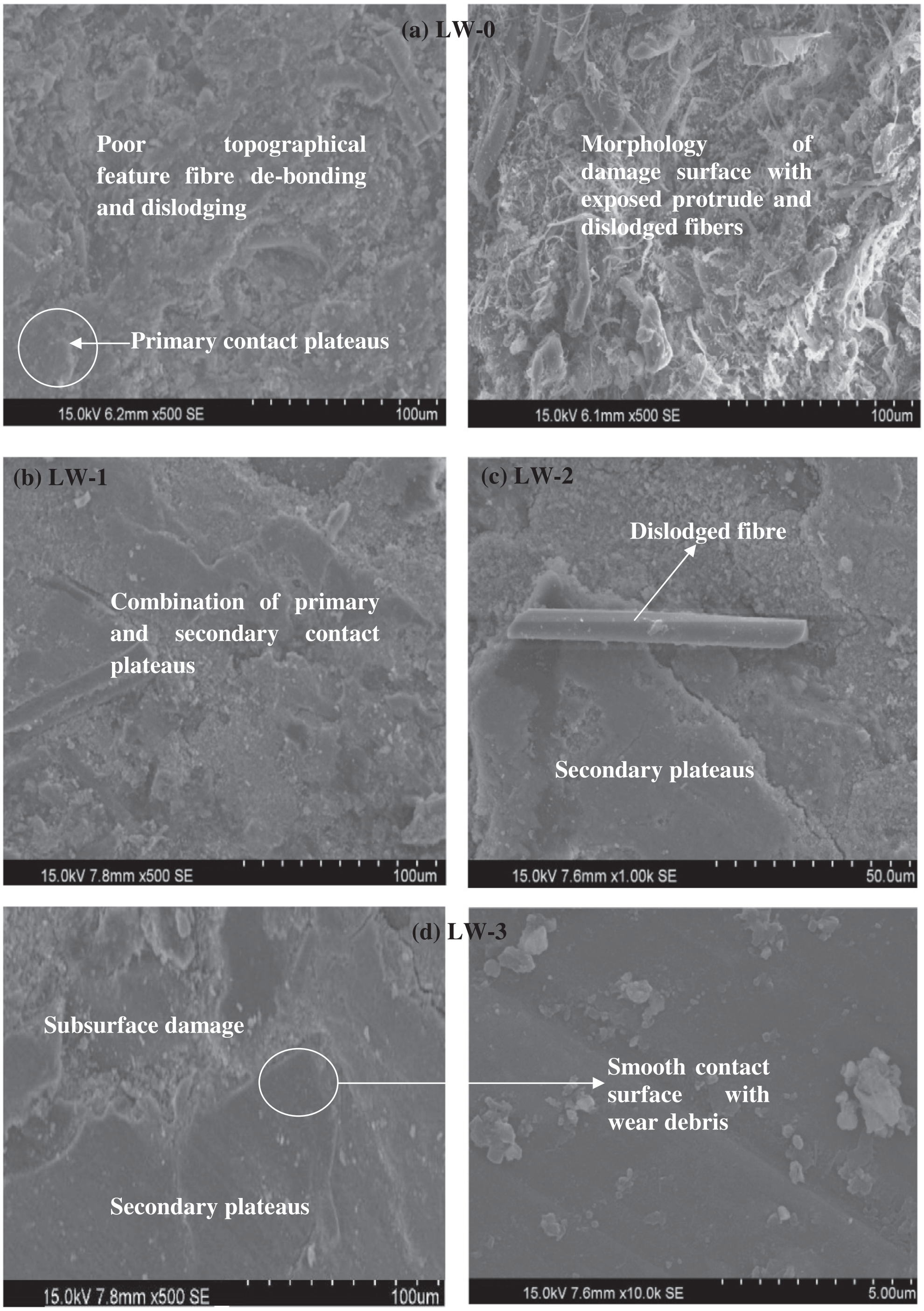

Figure 6 Worn surface micrographs of the composites (a) LW-0 (b) LW-1 (c) LW-2 (d) LW-3.

increase in dissipation of heat (i.e. low DTR) at higher wollastonite content. The composite having the highest lapinus content successfully arrests the highest rise in the disc temperature. This may be attributed to the dominant role of abrasive component of friction/wear due to the hard nature of lapinus fibre. However, the same composition is more effective in imparting the required frictional response by arresting fading even though the interface temperature reaches to its maximum. The disc temperature remained in the range of 663 ± 23 °C for the composites LW0/LW-1/LW-2 whereas, remained minimum (576 °C) for LW-3 composition having wollastonite fibre only. In the composites LW0/LW-1/LW-2 such an enormous temperature build-up phenomenon i.e. by more than ~70 °C from LW-3 composition is still adequately complemented by a very stable μ-recovery response (124 ± 12%), as a consequence of which their influence on the fade performance remained much lesser (37 ± 12%) than the composite LW-3 showing the highest fade i.e. ~70%. The lowest amount of fade is due to the presence of high lapinus fibre content in the composites (LW-0/LW-1/LW-2), which minimize the temperature induced decay effects while the highest extent of fade (LW-3) with the lowest disc temperature rise is attributed

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to the presence of wollastonite contents responsible for enhancing the shear thinning behaviour of the operating film at the braking junction. Thus, comprehensively the fade–recovery–temperature rise of disc is viscously dependent on the compositional variables.

3.2.5. *Wear performance of the friction composites*

Wear performance of the friction composites is measured in terms of wear volume (in cm^3), by taking into account the weight loss (in grams) of the composite before and after tribological characterization, followed by normalization with density. From Fig. 5, it is clearly seen that an increase in the wollastonite fibre content in formulation results in an increase in wear resistance of the composites indicating synergism between lapinus and wollastonite fibres. Also, higher wear resistance can be attributed to the increase in total fibre content which helps in the formation of topographical features such as primary and secondary contact plateaus which reduces the wear significantly.

3.2.6. *Worn surface morphology*

The wear surface morphology of the friction composites has been investigated by scanning electron microscopy (SEM). The micrographs of the worn surfaces of the composites in Fig. 6, show the distinct characteristics of the friction-film/contact-patch-formation; associated wear mechanisms responsible for wear behaviour that are in confirmation with the obtained experimental results in relation with composition variables. The wear is controlled by the formation of primary and secondary plateaus. The primary plateaus originating from the bulk of the composite are due to rubbing of the fibres and hard ingredients against the disc whereas, the secondary contact plateaus arise due to compaction of the wear debris due to braking load generated at the braking interface due to the development of interfacial shear stress, that largely consists of pulverized filler particles and organic part of the composition. The formation of secondary plateaus reduces the wear of the composites. The nature, distribution and extent of these plateaus depend upon the composite composition. The contact patch as seen in the wear surface morphology of the composites based on lapinus fibre alone (LW-0) has shown more of primary contact plateaus indicating harder constituents to be encountering the braking induced shear stress at the interface leading to a higher level of friction, ~0.4. The same composites reveal a rough surface morphology as indicated by the fibre de-bonding and pulled-out fibres resulting in poor wear performance (Fig. 5). However, in case of composites LW-1/LW-2/LW-3 with a decrease in lapinus content and increase in wollastonite content the wear surface morphology mainly consists of secondary contact patches (that are loosely adhered to the underneath subsurface) formed due to wear debris compaction. These secondary contact patches cause the generation of smoother friction film on the composite that is operational at the braking interface. The secondary plateaus in LW-1/LW-2/LW-3 have covered the original friction surface to a great extent, decreasing the loss of the ingredients during sliding and have resulted in lower wear as compared to LW-0. Friction composites LW-1/LW-2/LW-3 contain smooth surfaces covered by a strong friction film leading to an increase in the effective true contact area of the mating surfaces which decrease the effect of applied load and make them prone to thermal degradation, thereby causing higher fade and good recovery performance in LW-1/LW-2/LW-3 as compared to LW-0 as seen in Fig. 4. Thus, the presence of fibrous ingredients (lapinus and wollastonite) in friction formulation has a systematic influence on the mechanism of contact patch formation–reformation–destruction equilibrium and its associated alterations in topographical attributes that are found to be crucial in controlling the tribological response of the composites in friction braking situations.

4. Conclusions

Physical, chemical, mechanical and tribological properties of composite friction materials based on a combination of lapinus and wollastonite fibres have been evaluated. The tribological properties were evaluated on a Krauss friction testing machine by using a standard test protocol conforming to ECE R-90 regulation whereas, physical, chemical and mechanical properties were evaluated as per industrial standard. The following conclusions were drawn from the study:

- Increase in wollastonite content led to an increase in density and hardness whereas, increase in lapinus content that led to an increase in void content, heat swelling, water absorption and compressibility respectively.
- The performance coefficient of friction (μ_P) has been observed to be highest in the composite with the highest amount of lapinus fibre and decreasing consistently with the decrease in the lapinus fibre.
- The frictional fluctuations ($\mu_{max} - \mu_{min}$) have been observed to be lowest in the composite with the highest amount of lapinus fibre and found to be increasing consistently with the increased in wollastonite fibre.
- The fade performance remained highest in the composite with the highest amount of lapinus fibre and consistently decreasing with the decrease in the lapinus fibre.
- The recovery performance remained highest in the composite with the highest amount of wollastonite fibre and consistently decreasing with the increase in the lapinus fibre.
- The composite with highest amount of lapinus fibre shows the highest temperature rise of the disc, highest stability coefficient whereas composite with the highest amount of wollastonite fibre exhibits least variability coefficient.
- The wear performance was found to increase with the increase in wollastonite fibre, whereas it consistently decreased with the increase in the lapinus fibre.
- The study of worn surface micrographs by scanning electron microscopy (SEM) shows that differential contact plateaus proved crucial in controlling the tribo-performance of such friction composites.
- Overall, the increased lapinus fibre content was observed to enhance the friction performance, friction fade performance, friction fluctuations and friction stability performance; whereas, increased wollastonite fibre was observed to enhance the wear performance, recovery performance and friction variability of the friction composite.

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