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Fabrication, Microstructure, and Tribological Performance of High-Speed Brake Pad Composites: A Review

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Abstract : High-speed railway systems operating beyond 200 km/h demand friction brake materials capable of sustaining high thermal loads, stable frictional behaviour and reliable performance under emergency and routine braking conditions. With the development of high-speed corridors in India, the indigenisation of brake pad composites has gained importance for ensuring self-reliance in critical components. This study reviews the synthesis routes, material formulations and tribological responses of brake pad composites suitable for high-speed applications. Emphasis is placed on metal-matrix composite systems fabricated through powder metallurgy, owing to their favourable thermal conductivity, mechanical stability and consistent friction coefficient. Microstructural assessment using Scanning Electron Microscopy (SEM) and wear evaluation through pin-on-disk testing are planned to establish processing–structure–property relationships. The article further classifies brake pad materials used in modern high-speed rolling stock and examines the influence of tribofilm formation and surface evolution on braking efficiency. The review underlines the need for advanced composite formulations to address the operational demands of high-speed railways and supports ongoing efforts towards indigenous brake material development.

IndexTerms - High-speed railways; Friction brakes; Brake pad composites; Metal-matrix composites; Powder metallurgy; Tribology; Wear behaviour; Scanning Electron Microscopy (SEM); Pin-on-disc testing; Tribofilm formation; Thermal stability; Indigenous brake materials.

I. INTRODUCTION

The rapid expansion of high-speed railway networks has intensified the demand for braking systems capable of reliable operation at elevated velocities and thermal loads. High-speed trains operating beyond 200 km/h rely extensively on friction-based braking units to convert kinetic energy into heat, ensuring controlled deceleration during service braking, emergency stopping and gradient descent. The performance and safety of high-speed rolling stock are therefore closely linked to the stability, durability and thermal resistance of brake pad materials. In the context of India's ongoing development of high-speed rail corridors, the indigenisation of friction brake materials has assumed strategic importance. Traditional brake pad systems often depend on imported formulations, underscoring the need for locally developed, cost-effective and high-performance alternatives. Composite brake materials, particularly metal-matrix composite (MMC) systems, offer a promising pathway owing to their high thermal conductivity, stable friction coefficient and favourable mechanical characteristics. The tribological behaviour of brake pads governs their functional efficiency, as the braking interface undergoes complex surface transformations, including tribofilm formation, particle compaction and thermomechanical surface modification. Understanding these mechanisms is essential for designing materials that can sustain high-energy braking without excessive wear or performance degradation. Powder metallurgy has emerged as a suitable fabrication route for producing composite brake materials, providing precise control over composition, microstructure and reinforcement distribution. Microstructural characterisation using Scanning Electron Microscopy (SEM) and wear evaluation via pin-on-disc testing form an essential part of assessing the processing–structure–property relationships in such systems. During this short period of time due to enormous amount of heat, temperature of brake pad can rise sharply. The surface temperature will reach 500 °C and the flash temperature could run up to 900 °C **[1,2]**. This article reviews the material formulations, synthesis approaches and tribological characteristics of brake pad composites relevant to high-speed railway applications. The focus is on identifying material systems and processing routes that can support indigenous development of high-performance brake pads for modern rail transportation.

2.Friction Materials and Tribology

Quality of a brake pad can be controlled by changing the ingredients of friction material which are key constituents in the brake pad formulation. In this way, they guarantee safe braking operation for the high-speed train. Constituents of friction material are namely matrix, abrasives, lubricants, fillers etc. A robust brake pad material should have following characteristics like steady coefficient of friction, good thermal characteristics, minimum wear rate, high mechanical strength, low squeal and ability to perform in all weather conditions. Therefore, brake pad materials must be carefully selected so that they can have all the desired characteristics necessary for railway braking during high speed.

Tailoring the material to match the good quality friction railway brake pad requirement is not easy, it requires proper selection, experimentation on small and full scale. Metal matrix composites (MMCs) are promising candidates for high temperature wear applications such as in jet engines, gas turbine seals and bearings, brakes and clutches [3]. From the literature review it has been commonly observed that in high-speed railways all over the world commonly used metal-matrix composite (MMC) as their base material for brake pads which can withstand the high temperature and pressure. Numerous ingredients are used to achieve stabilized friction coefficient, low wear rate, low noise, high thermal conductivity, high strength for excellent braking performance. Therefore, it is important to optimize the formulation of brake pads and find suitable metal powders, additives etc. to maximize the frictional forces and minimize wear during emergency braking performance under heavy load and high-speed conditions. Efforts are under process to modify surface layer by making new formulations adding two or more reinforcements using industrial wastes categorized as hybrid metal matrix composite which can produce synergistic effect. Brake materials can be classified as shown in Table 1:

Table 1: Constituents of Brake Pad Formulations

Class	**Function**	**Ingredients**
Friction Modifier/Abrasives	Friction stability	Cr_2O_3, Graphite, MoS_2, Sb_2S_3, Al_2O_3, SiO_2, ZrO_2
Fillers	Functional fillers are added to improve properties and cut cost	$CaCO_3$, $BaSO_4$ etc.
Matrix Material	Binds ingredients together	Metallic, Organic, C-C friction

Constituents in the brake pad formulation can be classified according to the functions they perform in different categories. One of the important category is of fibres under which comes ingredients like Carbon fiber, steel fiber, PAN, Aramid, Rockwool etc. But there is a need to incorporate novel additives which can have characteristics of high elastic modulus, high strength, stable chemical properties and resistance to carbonization, which can strengthen the matrix and endow the composite with good mechanical properties **[4]**. Nowadays, material scholars replaced trial and error iterations by certain decision criteria's (Hardness, Friction Coefficient, Friction Stability, Specific Wear rate, Density) which help in making material selection whenever there are many alternatives which are conflicting in nature.

2.1 Tribology of brake pads

Tribology in the case of high-speed braking is governed by interaction among three components brake pad surface, disk surface and tribofilm formed between the two surfaces of brake pad and brake disk. In our study, increasingly more consideration has been centred around the tribological behaviour of brake pads under various initial velocities, particularly emergency braking. Due to friction between brake pad and brake disk various structures are formed on the surface of brake pad and a thin tribofilm is also formed which have considerable influence on coefficient of friction. Then, a series of physical and chemical changes occur in the surface layer under the combined action of friction force and heat, including plastic deformation, mechanical mixing, micro- crack initiation and propagation, oxidation, graphite lubricating film formation, transfer and delamination **[5]**. Various structures formed consisting of elastic highlands, lowlands, deformable and non-deformable contact plateaus are formed due to wear between the brake pad and disk.

This literature reviewed consist of three parts. As a first step, research papers of different brake pad formulations focussing high speed railways applications are surveyed. In second step, research papers related to tribology and vibrational response during braking was reviewed. In third step, papers related to brake formulations using Industrial wastes are reviewed to study possible formulations.

3.1 Chemical composition, physical and mechanical properties of brake pads used in High-Speed Railways

Xiao et al. [6]

This work focusses on the fabrication of metal matrix composites based on copper for high-speed train with special emphasis on their mechanical properties. The method of fabrication selected for their production was powder metallurgy. Formulation of the brake pad not consisted of copper but also iron as matrix material along with abrasives like Zirconium dioxide and iron carbide which imparted steadiness in coefficient of friction (0.40). Lubricants like graphite and molybdenum sulphide were also used Table 2. Inclusion of Iron in copper resulted in formation of Gray white iron due to which the composite can perform at elevated temperatures where copper becomes soft. Hardness was tested using a Brinell hardness testing machine. A full-scale dynamometer was used to study the tribology of Cu based brake pads. Characterisation was done using energy dispersive, scanning electron microscope, energy dispersive x-ray spectroscopy, wear rate reached 0.20 cm^3/MJ due to delamination wear mechanism. Testing on full scale dynamometer setup is costly and not easily accessible. Study of counter brake disk, XRD characterisation is missing.

Table 2: Chemical composition of Cu-MMC in high-speed trains [6]

Chemical composition of Cu-MMC							
Element	Cu	Fe	Graphite	MoS_2	ZrO_2	FeCr	Others
Content in Wt%	40 – 55	10 – 12	17-19	2 – 3	6 – 8	6 – 8	4 – 10

Zhang et al. [7]

This work focusses on the investigation of developed copper-based brake pads by changing the iron powder content in the composite material using a braking protocol on a dynamometer for wear. The method of fabrication was using powder metallurgy. The composition consisted mainly of three types of iron powders namely copper coated Fe, carbonyl iron and plate like Fe in Table 3. Using these three iron powders nine composite samples were made each showing different coefficient of friction when tested on dynamometer. A novel braking protocol was developed which tested samples at different braking speed, pressure and frequency. Most suitable sample in terms of steady coefficient of friction is one having 30.6% copper coated iron powder. Characterisation was done by scanning electron microscope, energy dispersive X-ray spectroscopy and X-ray diffraction. Study of counter brake disk is missing.

Table 3: Chemical compositions of the specimens with varied contents of iron powder (wt.%)

	Cu	Graphite	CCF	CBF	PF	MoS_2	SiO_2	CrFe	Others
CCF1	48.1	10	25.9			2	2	6	6
CCF2	43.4	10	30.6			2	2	6	6
CCF3	38.7	10	35.3			2	2	6	6
CBF1	52	10		22		2	2	6	6
CBF2	48	10		26		2	2	6	6
CBF3	44	10		30		2	2	6	6
PF1	52	10			22	2	2	6	6
PF2	48	10			26	2	2	6	6
PF3	44	10			30	2	2	6	6

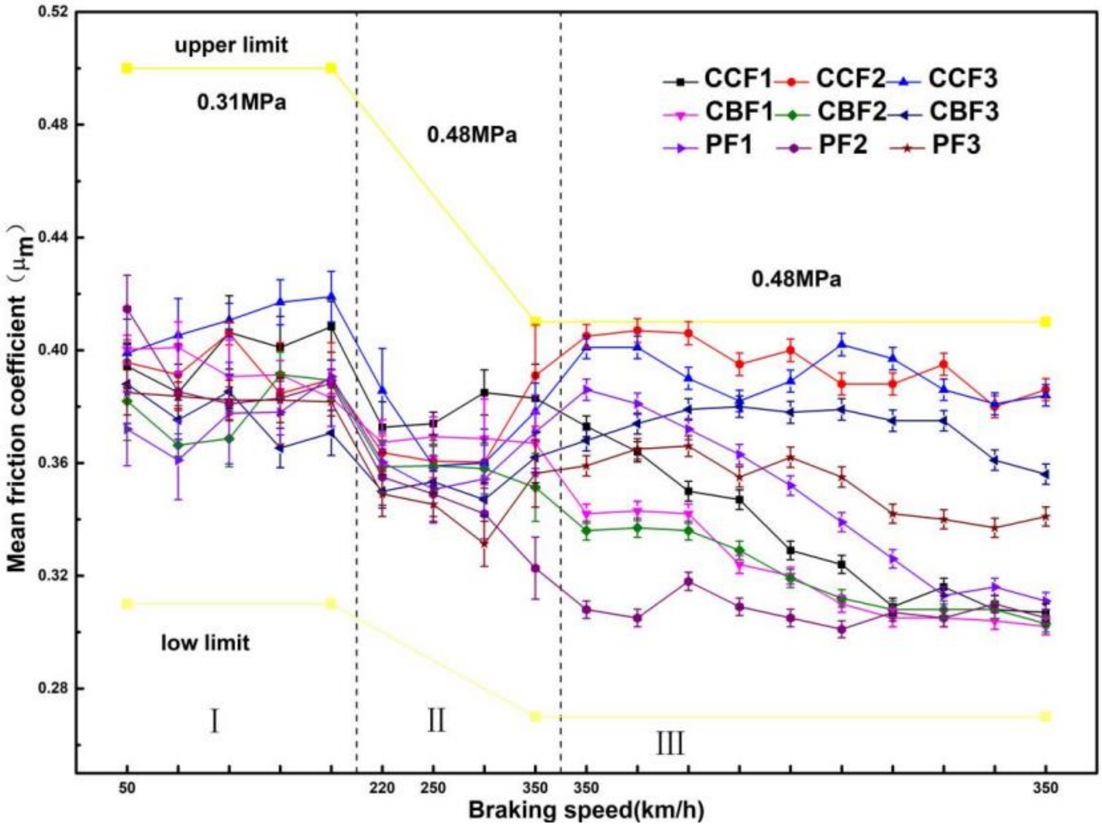
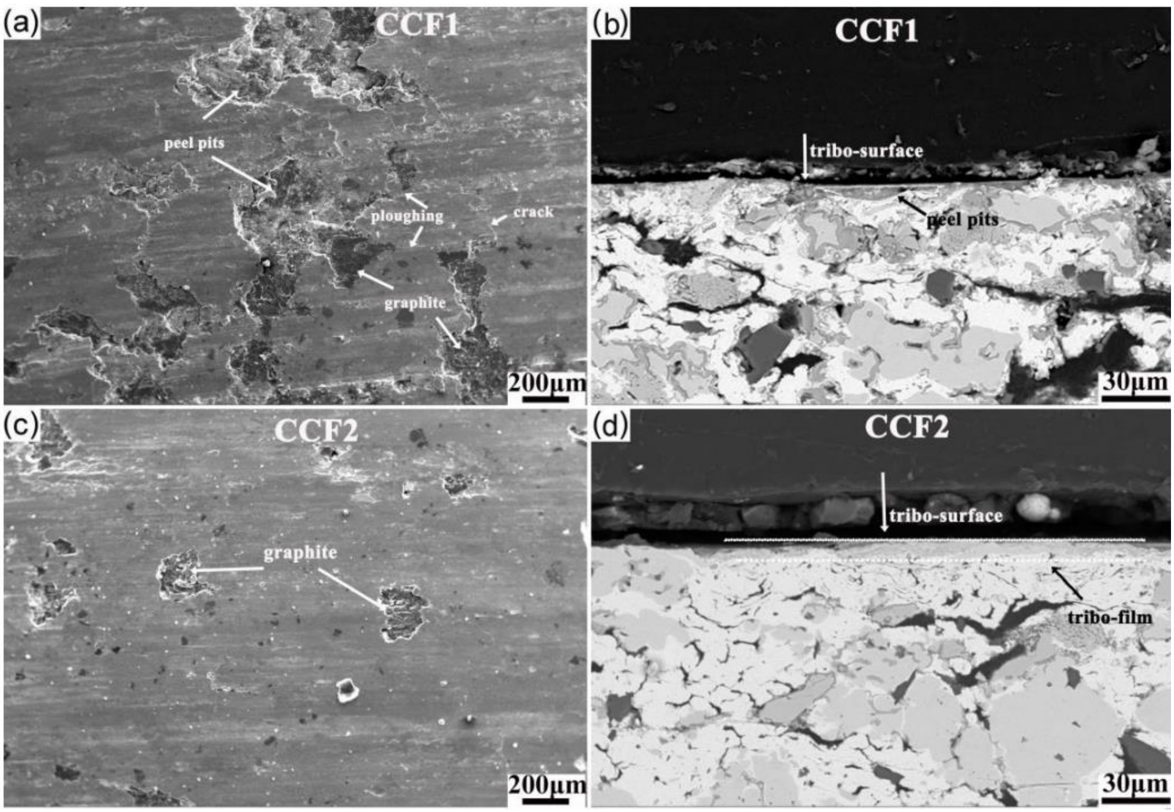


Figure 1. Plot of braking speed vs mean friction coefficient



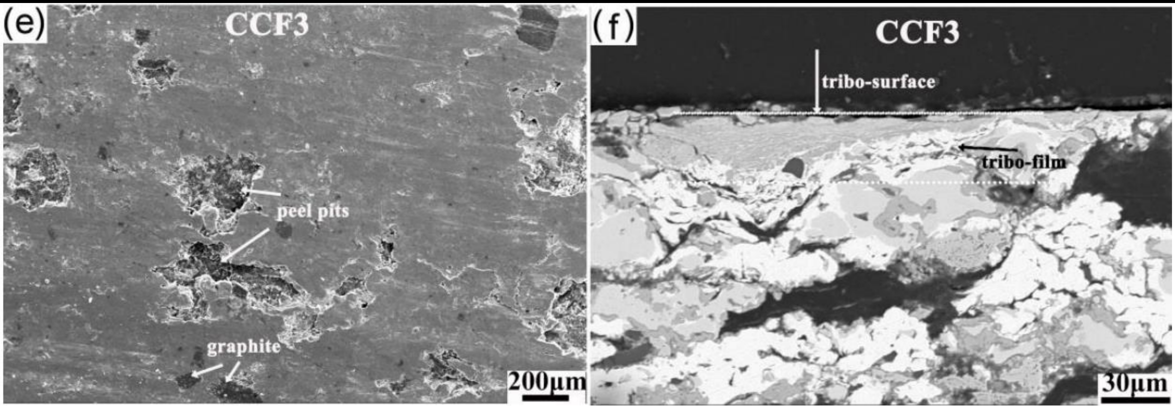


Figure 2. SEM images showing worn surface.

Ma et al. [8]

This work focusses on the study of interaction between C/C-SiC brake disk and two brake pads one of iron and other of copper. The method of fabrication of brake pad was using powder metallurgy and brake disk was using chemical vapor infiltration. Hardness of the copper brake pad was 20 HBW, Iron brake pad was 30 HBW and C/C-SiC brake disk was 90 HBW. The composition of two brake pads consisted mainly chromium, graphite and iron-chromium. Characterisation was done by scanning electron microscope, confocal microscopy, X-ray photoelectron spectroscopy and X-ray diffraction. Lab scale dynamometer was used to measure responsiveness of the Iron and Copper brake pads. It was found that Iron brake pad was more responsive to speed while Copper brake pad was more responsive to braking pressure. Coefficient of friction of Copper brake pad was 0.50 and of iron brake pad was 0.46. Adhesion is prevalent in Copper brake pads while abrasion exists in Iron brake pads. Existence of open pores on the brake pad surface helps to gather debris created during wear.

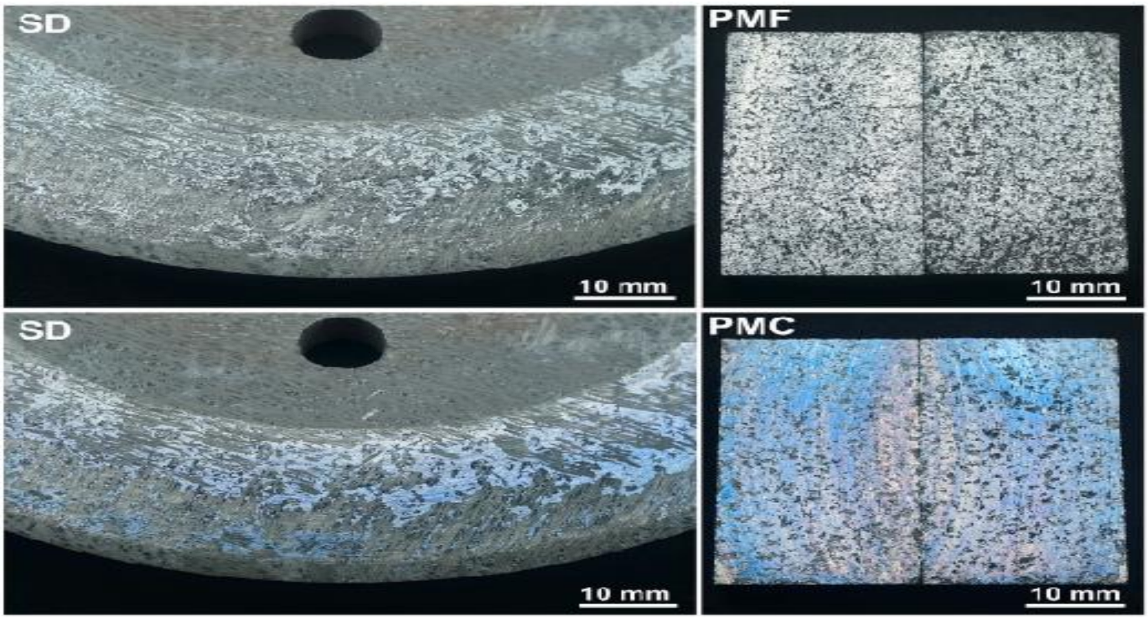


Figure 3: Macro morphologies of SD-PMF and SD-PMC after braking test **[8]**

Zhang et al. [9]

This work focusses on the development of copper composite brake pads consisting of varying concentration of carbon fiber (0-1.2%) mate with alloy steel disk. The method of fabrication of brake pad was using powder metallurgy. Graphite and Molybdenum disulphide were also added as lubricants. Brinell Hardness of the 0.4 wt% CF copper brake pad was 24.1±0.8 (Table 4). Characterisation was done by scanning electron microscope, energy dispersive X-ray spectroscopy, X-ray diffraction, laser scanning microscopy and electron microprobe microanalyzer. Cementite was observed when carbon fibre interacts with carbon fibre which was also responsible for a strong tribo film. Reduced scale dynamometer was used to measure responsiveness of the four samples of copper brake pad having different carbon fibre percentage at different braking pressure and speed. It was found that copper composite containing 0.4% Carbon fibre have greatest and steady coefficient of friction in the range of 0.357-0.372.

Table 4: Chemical compositions of Cu-based brake pads with different carbon content

Chemical compositions of Cu-based brake pads (wt.%)									
	Copper	CrFe	MoS_2	Fe	Graphite	CF	Others	Density	Hardness
CF0	55	8	2	18	10	0	6	5.08±0.03	21.5±0.5
CF0.4	55.6	8	2	18	10	0.4	6	4.96±0.05	24.1±0.8
CF0.8	55.2	8	2	18	10	0.6	6	4.93±0.02	13.6±1.1
CF1.2	54.8	8	2	18	10	1.2	6	4.76±0.07	13.2±1.0

Zhang et al. [10]

This work focusses on the development of copper composite brake pads consisting of granular and flake graphite (0-10.0 %). The method of fabrication of brake pad was using powder metallurgy. Tin and Molybdenum disulphide were also added Table 5. Brinell Hardness was directly proportional to the amount of granular graphite present as shown in Figure 4. Characterisation was done by scanning electron microscope, energy dispersive X-ray spectroscopy, laser scanning microscopy and pressure sensitive film. Pin on disc test was used to measure friction and wear. Flaky graphite was better fixed in the friction material in comparison to granular graphite through which crack initiation took place. When the sample have granular and flake graphite were equal in proportion i.e., 5% wt. coefficient of friction peaks in comparison other three samples. Specific wear rate is lowest for sample containing highest amount of granular graphite i.e., 10% wt. Study on lab scale dynamometer is missing.

Table 5: Chemical compositions of Cu-based friction materials

	Cu	**Sn**	**Fe**	**CrFe**	**SiO_2**	**Others**	**GF**	**GG**
GG0	56	1	18	6	2	7	10	0
GG3	56	1	18	6	2	7	7	3
GG5	56	1	18	6	2	7	5	5
GG7	56	1	18	6	2	7	3	7
GG10	56	1	18	6	2	7	0	10

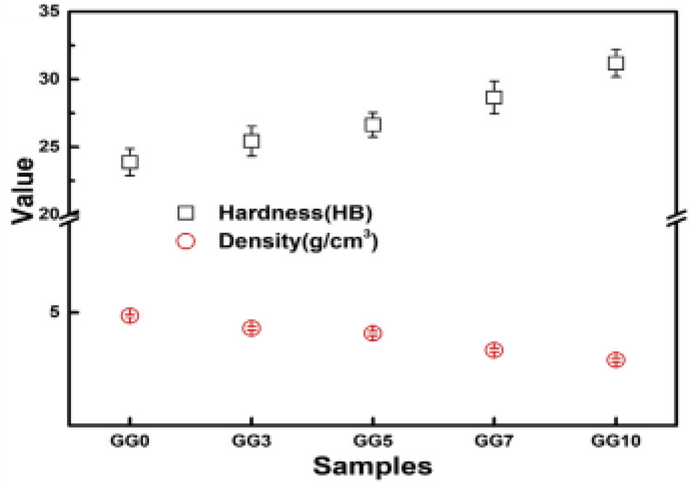


Figure 4. Brinell hardness and density of different composites

Zhang et al. [11]

This work focusses on the development of copper composite brake pads consisting of molybdenum disulphide (0-10.0 %) as lubricant. The method of fabrication of brake pad was using powder metallurgy. Iron and Graphite were also added Table 6. Brinell Hardness as shown in Fig 3. Characterisation was done by scanning electron microscope, energy dispersive X-ray spectroscopy, laser scanning microscopy, X-ray diffraction and transmission electron microscope. Reduced scale dynamometer was used to measure friction and wear. Composite sample carrying 2 wt% molybdenum disulphide was found to show peak in coefficient of friction and minimum wear. When copper interacts with MoS_2, $Cu_{1.92}S$ and $Cu_2Mo_6S_8$ are formed which cause abrasive wear. While when iron interacts with MoS_2, FeS was formed which act as lubricant reducing coefficient of friction. Reduced scale dynamometer was used to measure responsiveness of the six samples of copper brake pad having different MoS_2 percentage at different braking pressure and speed.

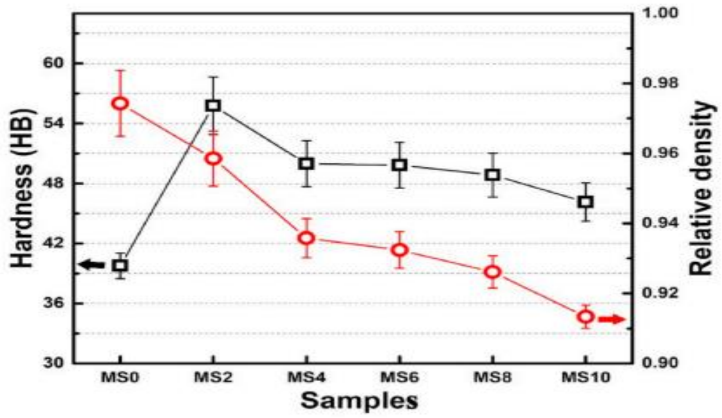


Figure 5. Brinell hardness and relative density of different samples [12]

Table 6: Chemical compositions of Cu-based brake pads (wt.%)

	Cu	Fe	Graphite	MoS_2
MS0	60	30	10	0
MS2	58	30	10	2
MS4	56	30	10	4

MS6	54	30	10	6
MS8	52	30	10	8
MS10	50	30	10	10

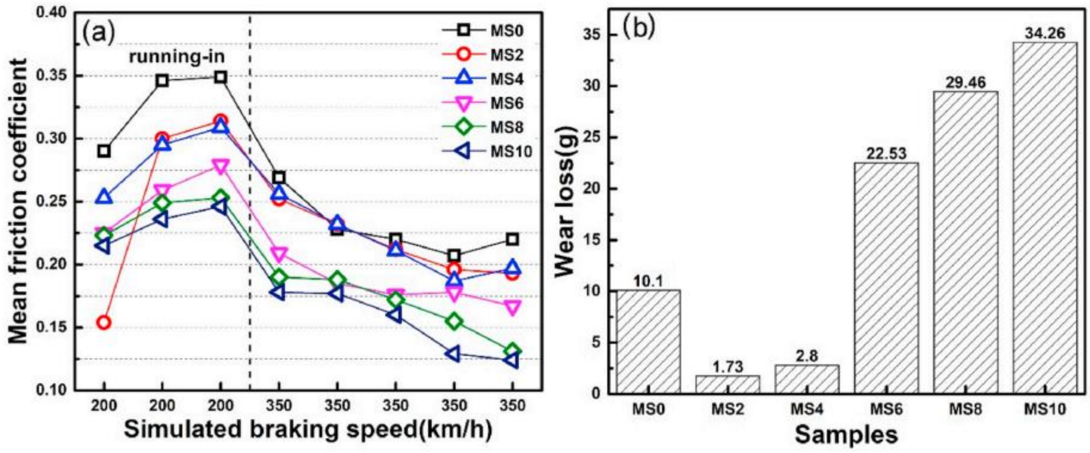
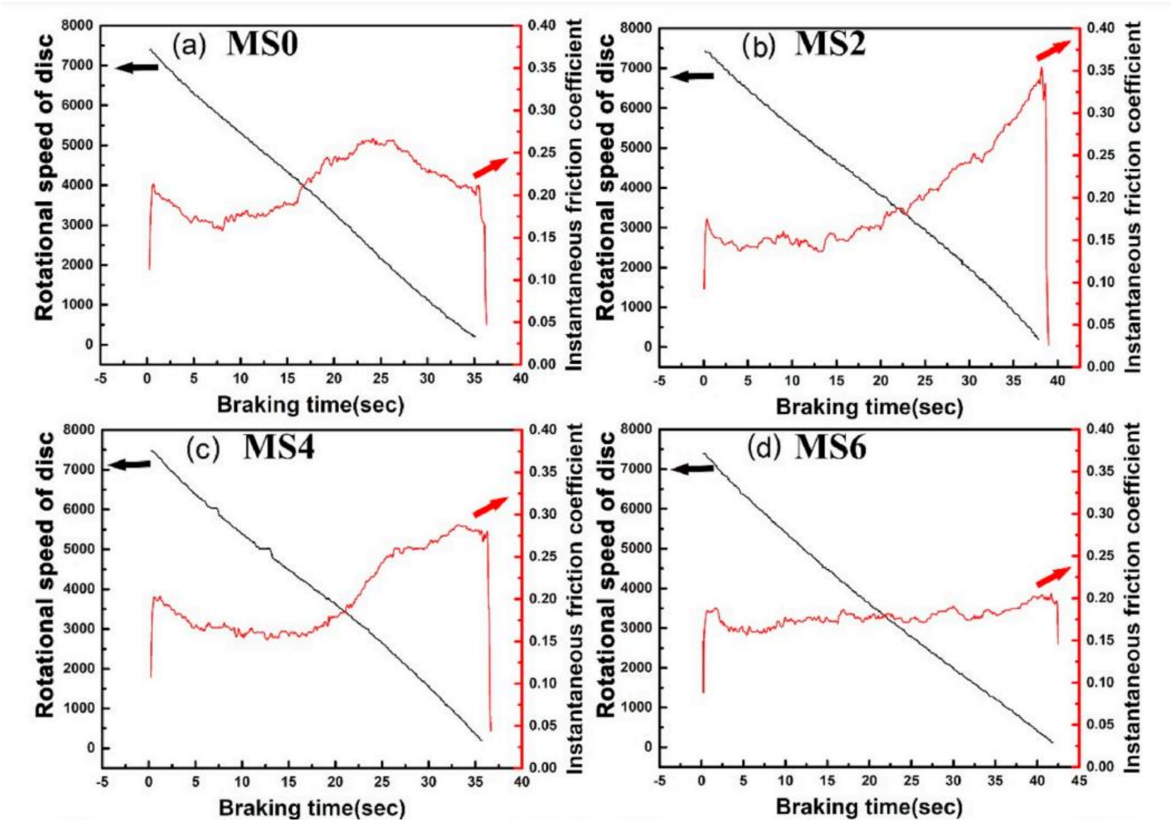


Figure 6. Plot of (a) simulated braking speed vs mean friction coefficient.

(b)samples vs wear loss.



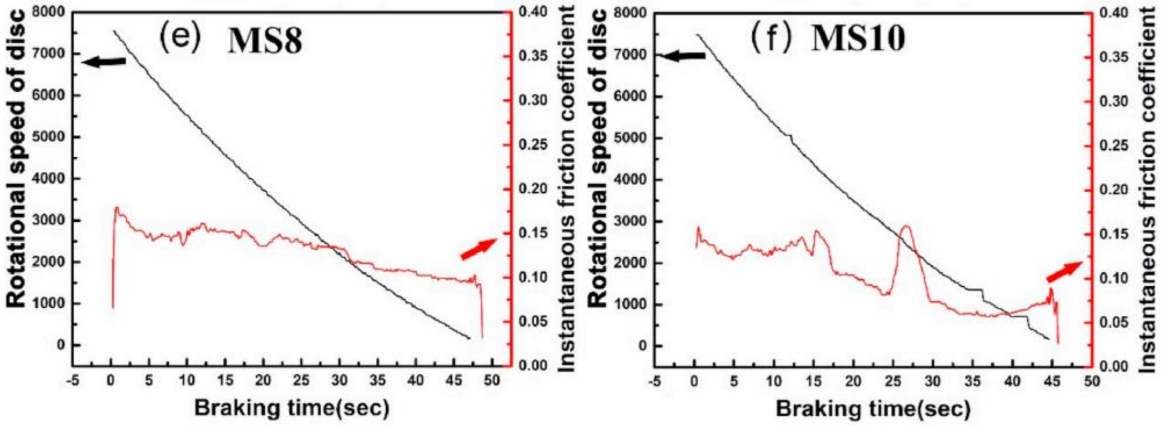


Figure 7. Variation of rotational speed of disc and instantaneous friction coefficient of different samples during the last braking at 350 km/h: (a) MS0; (b) MS2; (c) MS4; (d) MS6; (e) MS8 and (f) MS10.

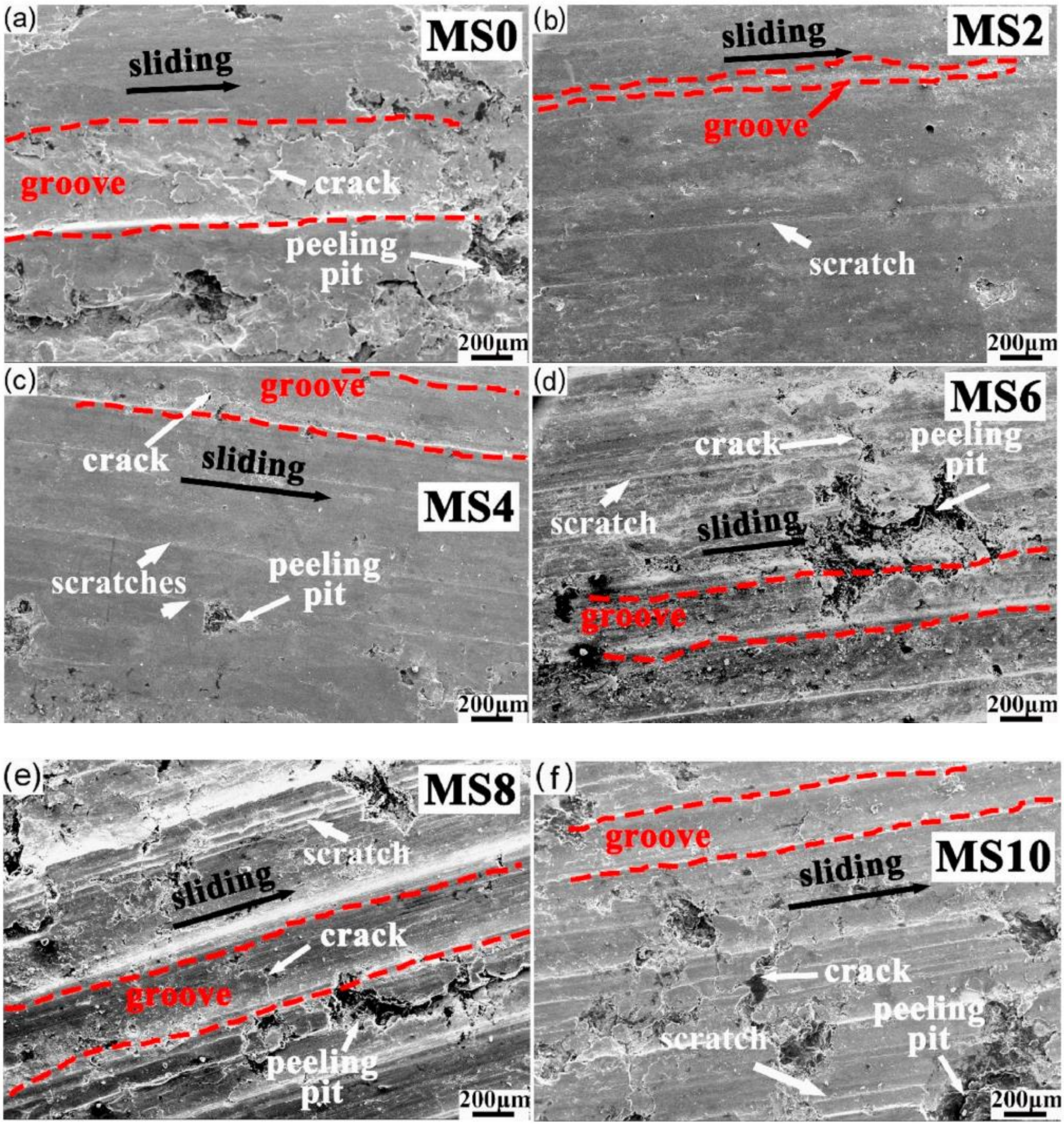


Figure 8. SEM images of friction surface of different samples after the whole testing: (a) MS0; (b) MS2; (c) MS4; (d) MS6; (e) MS8 and (f) MS10

Zhang et al. [12]

This work focusses on the development of copper composite brake pads consisting of nickel coated graphite flake (10.0 %) as lubricant mated with alloy steel. The method of fabrication of brake pad was using powder metallurgy. Tin and nickel coated graphite were added in Table 7. Brinell hardness of nickel coated graphite composite was higher than the uncoated one. Characterisation was done by scanning electron microscope, energy dispersive X-ray spectroscopy, laser scanning microscopy, X-ray diffraction. Nickel coated graphite was properly distribution in the copper brake pad which resulted. While when iron interacts with MoS_2, FeS was formed which act as lubricant reducing coefficient of friction in uniform coefficient of friction. Composite sample carrying 10 wt % nickel coated graphite was found to non-deviation in coefficient of friction at extreme speeds and pressure. Reduced scale dynamometer was used to measure coefficient of friction at different pressure and speeds. Wear was less noticeable in Nickel coated graphite in comparison to normal graphite. Delamination occurs in Nickel coated graphite.

Table 7: Chemical compositions of Cu-based brake pads (wt %)

	Cu	Sn	Fe	Ni	Graphite	SiO_2	CrFe	Other
GF	56	2	18	3	7	2	6	6
NGF	56	2	18	----	10(Ni Coated)	2	6	6

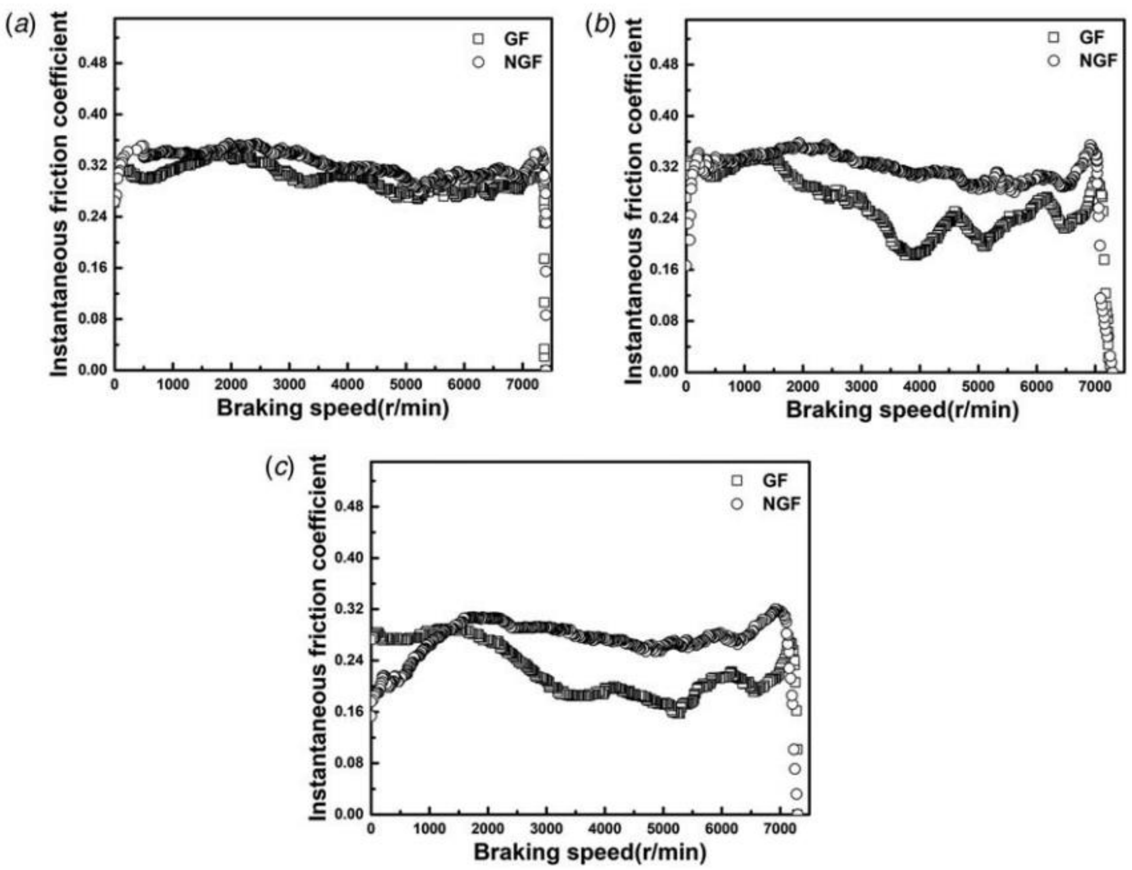


Figure 9. Instantaneous friction coefficient of NGF and GF test at 350 km/h and varied pressures: (a) 0.5 MPa, (b) 1 MPa, and (c) 1.5 MPa

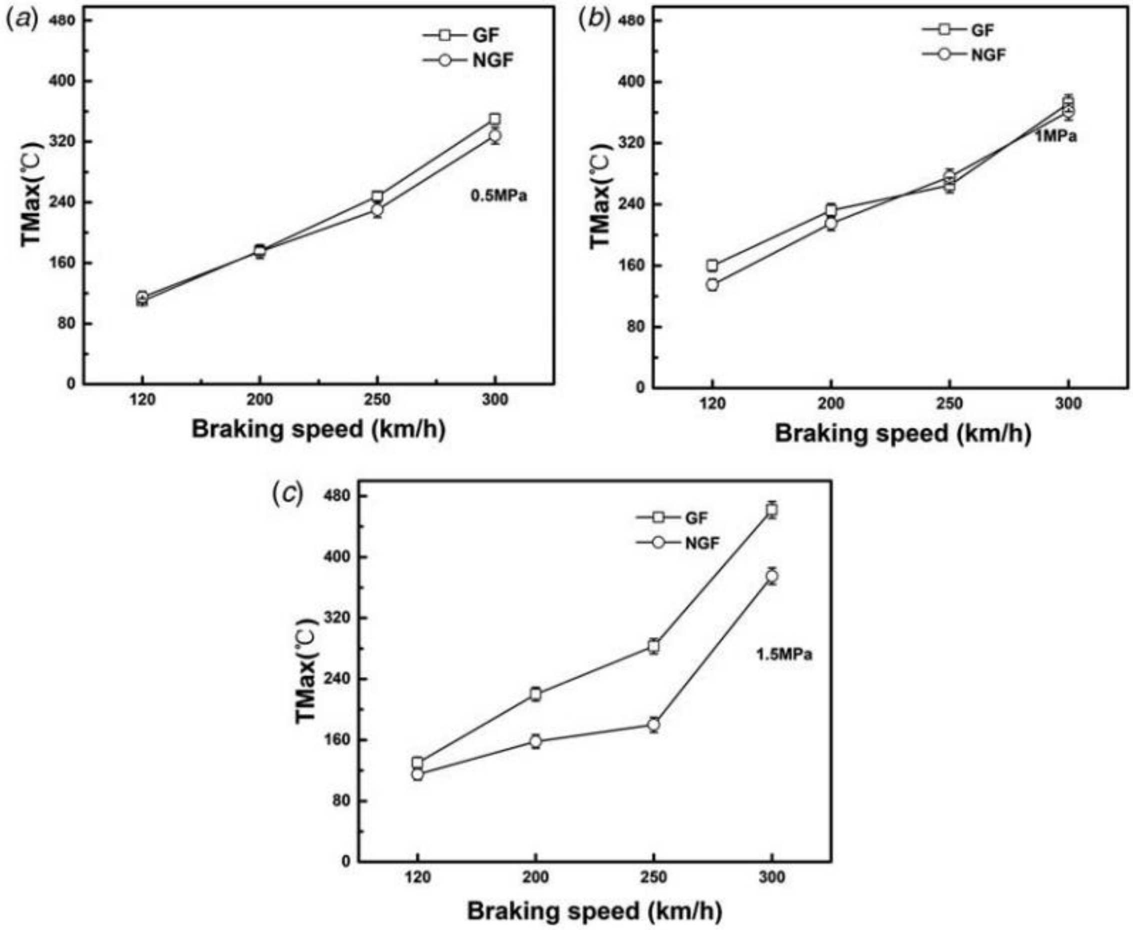


Figure 10. Maximum temperature of the brake pads tested at varied pressures: (a) 0.5 MPa, (b) 1 MPa, and (c) 1.5 MPa

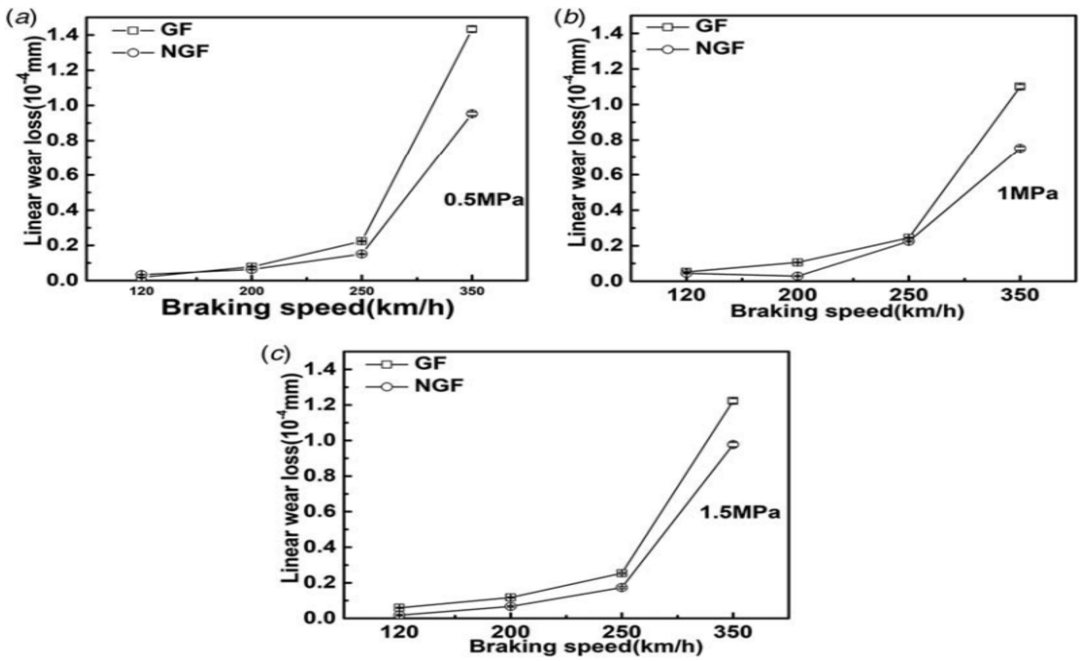


Figure 11. Linear wear loss at different braking speeds and pressures: (a) 0.5 MPa, (b) 1 MPa, and (c) 1.5 Mpa

Table 8: Friction coefficient and linear wear loss of the composites tested at different pressures and braking speeds

Experiment number	X_1 (MPa)	X_2 (km/h)	$X_1 \times X_2$	μ_{mGF}	μ_{mNGF}	LW_{GF} (10^{-4} mm)	LW_{NGF} (10^{-4} mm)
1	0.5	120	60	0.33	0.34	0.02	0.03
2	0.5	200	100	0.36	0.35	0.08	0.06
3	0.5	250	125	0.36	0.37	0.22	0.15
4	0.5	350	175	0.3	0.32	1.43	0.95
5	1	120	120	0.37	0.34	0.05	0.05
6	1	200	200	0.38	0.36	0.11	0.03
7	1	250	250	0.35	0.35	0.24	0.23
8	1	350	350	0.26	0.32	1.1	0.75
9	1.5	120	180	0.36	0.32	0.06	0.02
10	1.5	200	300	0.36	0.33	0.12	0.07
11	1.5	250	375	0.28	0.28	0.25	0.17
12	1.5	350	525	0.22	0.28	1.22	0.98

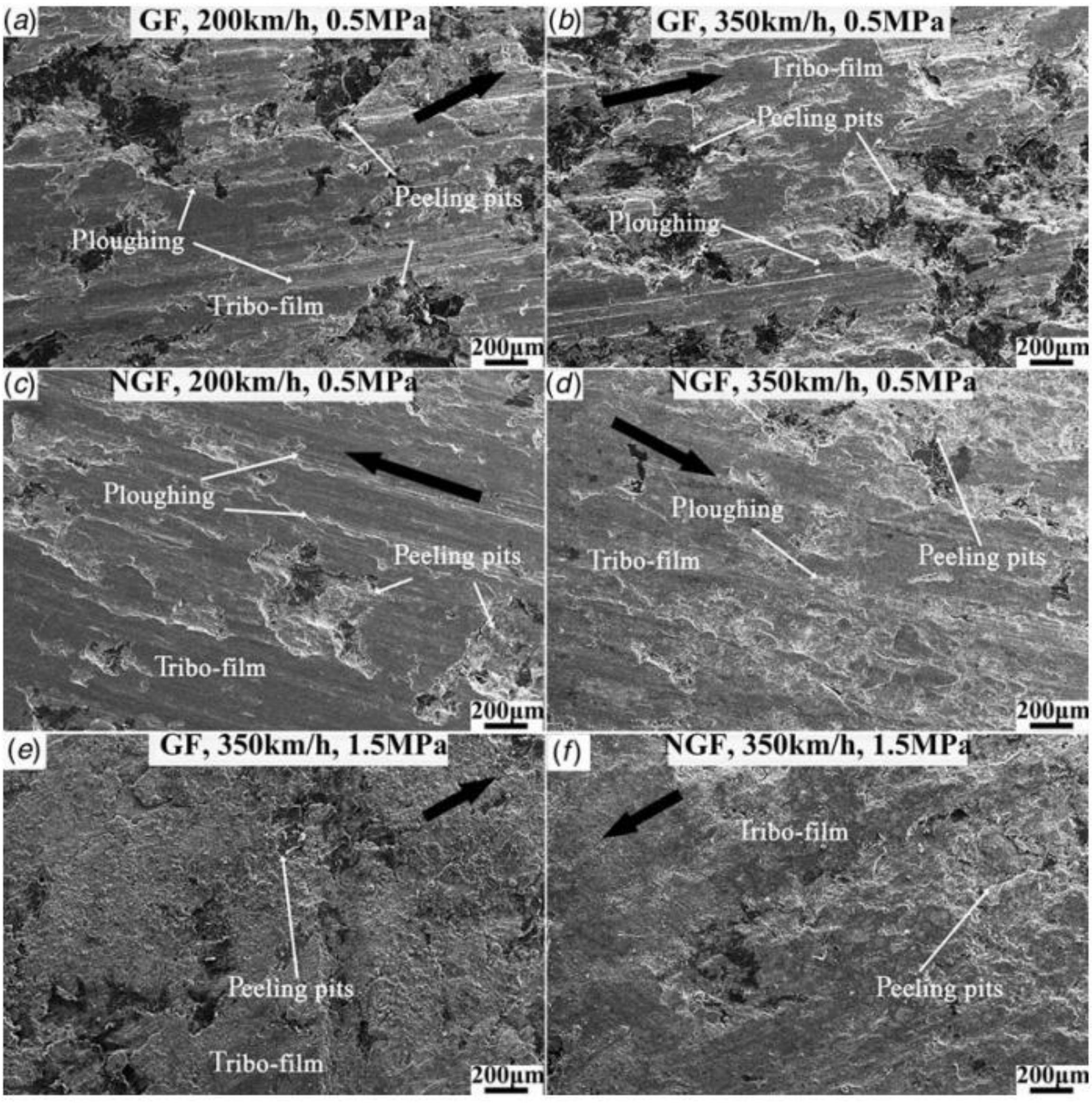


Figure 12: SEM image of the worn surface of the brake pad.

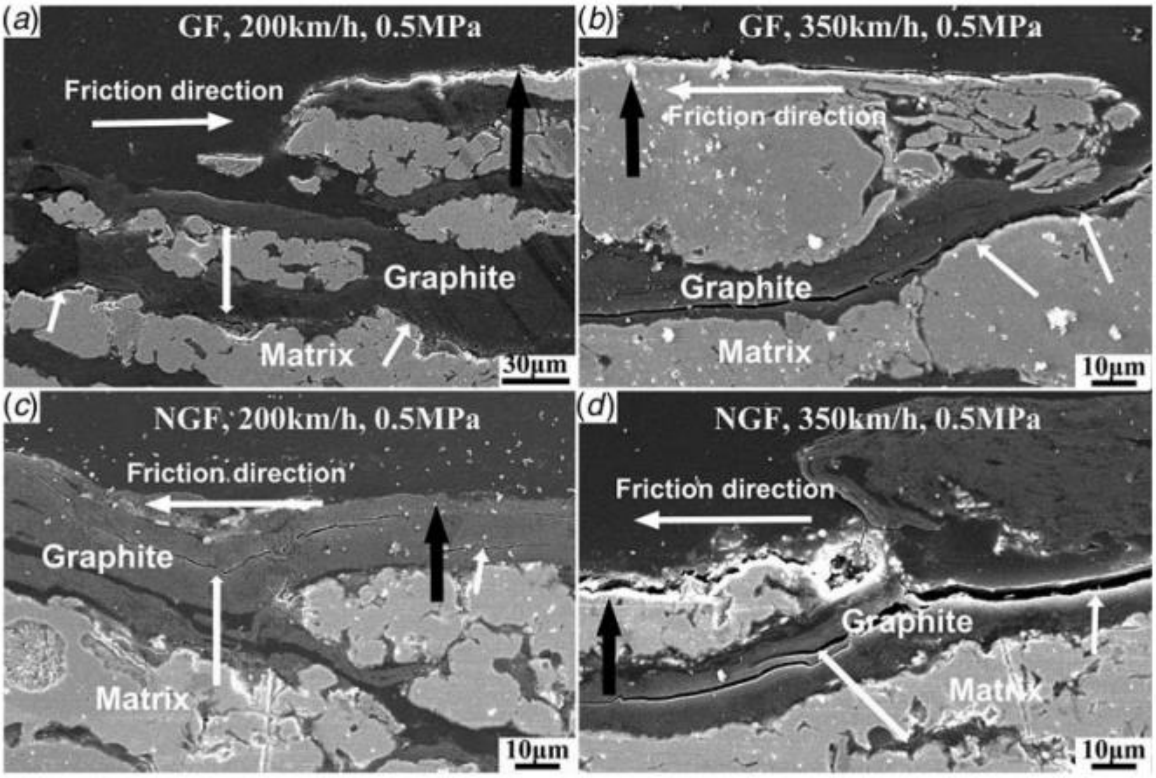


Figure 13. SEM images of the graphite near the worn surface tested at 0.5 MPa and varied braking speeds: (a) GF, 200 km/h; (b) GF, 350 km/h; (c) NGF, 200 km/h; and (d) NGF, 350 km/h. The white arrows indicate the cracks and the black arrows indicate the worn surface.

Asif et al. [13]

This work focusses on the development of iron composite brake pads accompanied by copper powder (10.0 %). The method of fabrication of brake pad was using powder metallurgy and hot powder pre-form forging technique. Phosphorus, Graphite and Antimony trisulfide were also added in Table 9. Brinell Hardness of first formulation out of five samples was highest in Table 9. Characterisation was done by scanning electron microscope, energy dispersive X-ray spectroscopy. We can observe from table that formulation 1 have poor wear resistance in comparison to formulation 2 and formulation 4. Formulation 2 coefficient of friction peaks. Sub scale dynamometer was used to measure the coefficient of friction and wear.

Table 9: Density and Hardness measurement

Samples	FA01	FA02	FA03	FA04	FA05
Density ρ(gm/ cm^2)	5.2	5.4	5.7	5.8	5.7
Hardness (BHN)	94	69	78	79	84

Table 10: Chemistry of friction elements along with backing plate.

samples	Wear (gm)	Coefficient of Friction (COF)			Temperature	Noise Level, (dB)		
		Max.	Min.	Avg.	°C	Max.	Min	Avg.
FA01	0.63	0.38	0.35	0.365	116	38	34	36.0
FA02	0.49	0.58	0.53	0.555	168	35	32	33.5
FA03	0.61	0.39	0.38	0.385	145	30	29	29.5
FA04	0.42	0.48	0.47	0.475	169	36	30	33.0
FA05	0.64	0.46	0.45	0.455	151	32	28	30.0

Table 11: Chemical composition of friction elements along with backing plate

Chemistry of friction elements along with backing plate				
Symbol	Metallic constituents	Ceramic Constituents	Lubricants	Backing Plate
FA01	Fe-70.3, Cu-10, Sn-1	P-0.7,SiC-6	Graphite-7, Sb_2S_3-5	C-0.3,Cu –1.5, P -0.3, Fe-97.9
FA02	Fe-68.1, Cu-10, Sn-2	P-0.4,SiC-3.5, Ceramic wool-1	Graphite-7, Sb_2S_3-5	
FA03	Fe-68.7, Cu-10,Sn-1	P-0.8,SiC -3.5	Graphite8,Sb_2S_3-1, $BaSO_4$-6	
FA04	Fe-69.6, Cu-10, Sn-1	P-0.4,SiC -6, Ceramic wool-1	Graphite8,Sb_2S_3-1,BaSO4-3	
FA05	Fe-73.7, Cu-10, Sn -3	P-0.8, SiC -3.5	Graphite-6, Sb_2S_3- 1, $BaSO_4$-3, $CaSO_4$- 1	

Bijwe et al. [14]

This work focusses on the development of two types of brake pads one using powder and other using fiber of copper. The method of fabrication of brake pad was using powder metallurgy. Barite was also added in composition Table 12. Hardness and density of the various compositions was shown in Table 13. Characterisation was done by scanning electron microscope. Full scale dynamometer was used to measure coefficient of friction and wear of the sample composites. Powder sample found to be performed well in terms of imparting friction as they get uniformly spread over the friction surface making good tribolayer. Sample containing 20% wt copper powder shows highest opposition to wear.

Table 12: Design and designations of composites

Ingredients/designation	Powder series (dia: 280–430 µm)			Fiber series (length: 2.09–2.35 mm)		
	CP_0[a]	CP_1	CP_2	CF_0[a]	CF_1	CF_2
Copper (wt.%)	0	10	20	0	10	20
Barite (inert filler) (wt.%)	40	30	20	40	30	20
Parent composition[b]	60	60	60	60	60	60

C: copper, P: powder, F: fiber and subscripts 0, 1 and 2 for 0, 10 and 20 wt.% of copper content in composites, respectively.

Table 13: Physical, thermo-physical and mechanical properties of the composites

Properties	Ref[a]	CP_1	CP_2	CF_1	CF_2
Density (g/cc)	2.14	2.31	2.44	2.28	2.43
Porosity (%) (JIS D 4418:1996)	4.05	4.30	4.39	4.85	5.17
Acetone extraction (%)	1.34	1.18	1.31	1.27	1.39
Tensile strength (MPa) ASTM D 638	12.14	12.65	12.85	14.38	16.49
Young's modulus (GPa) ASTM D 638	2.19	2.30	2.00	2.84	2.96
Flexural strength (MPa) ASTM D 790	27.38	23.89	26.68	25.38	25.05
Flexural modulus (GPa) ASTM D 790	5.05	4.80	3.99	4.45	4.17
Rockwell hardness (S-scale) (ASTM D 785)	90–95	88–93	85–92	90–95	78–85
Compressibility (%) ISO 6310	0.68	1.02	1.09	0.73	1.74
Thermal conductivity ($W m^{-1} K^{-1}$)	1.55	2.41	2.57	2.3	2.49
Thermal diffusivity $\times 10^{-4} (cm^2 s^{-1})$	61	97	113	93	108
Specific heat ($J kg^{-1} K^{-1}$)	1187	1076	932	1085	949
Effusivity ($J m^{-2} K^{-1} s^{-1/2}$)	1985	2447	2316	2418	2385

Peng et al. [15]

This work focusses on the development of copper composite brake pads and studying the influence of adding abrasives. The method of fabrication of brake pad was using powder metallurgy. Titanium carbide and alumina were added in composition as abrasives Table 14. Hardness and density of the various compositions was shown in Table 15. Characterisation was done by X-ray diffraction, energy dispersive X-ray spectroscopy. At high-speed titanium carbide stick properly to the matrix thereby its friction increasing capacity is high in comparison to alumina. Full scale dynamometer was used to measure friction and wear of the sample composites.

Table 14: Chemical compositions of the samples (by vol%)

Group	Sample	Cu	Fe	Cr-Fe	Graphite	MoS_2	TiC	Al_2O_3
Basic	F0	38	18	10	30.0	4.0	--	--
	FTC-1	37.3	17.6	9.8	29.4	3.9	2.0	--
FTC	FTC-2	35.7	16.9	9.4	28.2	3.8	6.0	--
	FTC-3	33.5	15.8	8.8	26.4	3.5	12.0	--
	FAO-1	37.3	17.6	9.8	29.4	3.9	--	2.0
FAO	FAO-2	35.7	16.9	9.4	28.2	3.8	--	6.0
	FAO-3	33.5	15.8	8.8	26.4	3.5	--	12.0

Table 15: Physical and mechanical properties of braking pads [15]

Group	Sample	Density (g/cm^3)	Theoretical density (g/cm^3)	Relative density (%)	Porosity (%)	Brinell hardness (HB)
Basic	F0	4.57	6.37	71.7	16.3±0.2	12.7±0.7
	FTC-1	4.52	6.34	71.3	16.3±0.6	11.0±0.8
FTC	FTC-2	4.37	6.28	69.6	17.4±0.7	13.1±1.8
	FTC-3	4.26	6.19	68.8	18.9±0.5	13.1±0.6
	FAO-1	4.42	6.32	69.9	16.9±0.7	12.1±1.5
FAO	FAO-2	4.18	6.21	67.3	18.3±0.5	12.8±1.0
	FAO-3	3.90	6.06	64.4	20.1±0.8	12.0±0.1

Zhang et al. [16]

This work focusses on the development of copper composite brake pads using Al_2O_3 fiber (03 wt.%) mated with alloy steel. The method of fabrication of brake pad was using powder metallurgy. Graphite and molybdenum disulphide were also added as lubricants Table 15. Brinell Hardness of the copper brake pad was 22.7 ± 2.1 HBW. Characterisation was done by scanning electron microscope, energy dispersive X-ray spectroscopy, Laser Scanning Microscope. Reduced scale dynamometer was used to measure responsiveness of the Copper brake pads with speed and pressure. It was found that at higher braking speeds the temperature of copper brake pads containing Al_2O_3 fiber remains low and it promotes the formation secondary plateaus.

Table 16: Compositions of copper-based brake pads (wt. %)

	Copper	CrFe	MoS_2	Fe	Graphite	Additive	Others
AF	53	8	2	18	10	3% Al_2O_3 Fiber	6
0F	56	8	2	18	10	_	6

Table 17: Physical properties of copper-based brake pads

Samples	Density (g/cm^3)	Porosity (%)	Hardness (HB)	Shear strength (MPa)
AF	5.00 ± 0.07	19.5 ± 1.1	22.7 ± 2.1	37.18 ± 1.2
0F	5.26 ± 0.09	16.9 ± 1.4	27.3 ± 1.7	47.81 ± 1.1

Zhang et al. [17]

This work focusses on the development of copper composite brake pads using Cr and CrFe. The method of fabrication of brake pad was using powder metallurgy. Flake and granular graphite were also added as lubricants as shown in Table 18. Brinell Hardness of the copper brake pad was 19.4 ± 2.4 HBW. Characterisation was done by scanning electron microscope, energy dispersive X-ray spectroscopy. Reduced scale dynamometer was used to measure responsiveness of the Copper brake pads with speed and pressure. It was found that at higher braking speeds and temperature of copper brake pads sample containing 4% CrFe and 6% Cr performed well in terms of maintaining a stable coefficient of friction. Cr provides chemical stability to the tribofilm while CrFe bears the load**.**

Table 18: Chemical composition of Cu-based brake pads (wt%).

	Cu	Fe	C(flake)	C(Synthetic)	Cr	CrFe	Other
C10CF0	56	26	7	7	10	0	4
C8CF2	56	26	7	7	8	2	4
C6CF4	56	26	7	7	6	4	4
C4CF6	56	26	7	7	4	6	4
C2CF8	56	26	7	7	2	8	4
C0CF10	56	26	7	7	0	10	4

Zhang et al. [18]

This work focusses on the development of copper composite brake pads and study of their wear mechanism. The method of fabrication of brake pad was using powder metallurgy. Flake and Granular Graphite were also added as lubricants. Brinell Hardness of the copper brake pad was 18.7 HB. Characterisation was done by scanning electron microscope, energy dispersive X-ray spectroscopy. Pin on Disc setup was used to measure responsiveness of the Copper brake pads with speed and pressure. A heating chamber is located in the Pin on Disc setup. At different temperature copper matrix behaves differently. First below 600 °C the sample performs well in terms of coefficient of friction (0.35-0.45). Secondly when tested above 600 °C the graphite present helps to maintain the friction properties. Thirdly at 800 °C copper softens and losses its friction properties.

Table 19: Chemical composition of self-developed brake pads (SDBP)

Chemical composition of SDBP							
Element	Cu	Fe	CrFe	SiC	Flake Graphite	Granular Graphite	Others
Content in Wt%	56	18	8	2	5	5	6

Lin Zhang et al. [19]

This work focusses on the fabrication of copper brake pads consisting of copper coated silicon dioxide. The method of fabrication was powder metallurgy. Iron, Graphite were also added as shown in Table 22. Hardness of copper coated silicon dioxide brake pad was 23.2HB. Characterisation was done using scanning electron microscope and X-Ray diffraction. Reduced scale tribometer was used to measure friction coefficient and wear. It was found that copper brake pad containing copper coated silicon dioxide exhibits better friction coefficients and bonding to the matrix. It sticks well to the matrix thereby creates obstacle in movement of wear debris which in turn create secondary plateaus, reduce wear and fade at high temperature.

Table 20: Chemical compositions of the copper-based brake pads (wt.%)

	Cu	**Fe**	**SiO_2**	**Cu-Coated SiO_2**	**graphite**	**CrFe**	**Sn**	**Others**
SD	55.5	18	2	-	10	8	0.5	6
Cu-SD	53.5	18	-	4	10	8	0.5	6

Wong et al. [20]

Brake pad is a very heterogenous friction material consisting of multiple phases and complex microstructure of more than 20 different constituents for applications in the high-speed railway industry.

Figure 14. Brake pad composite of different compositions used in high-speed trains.

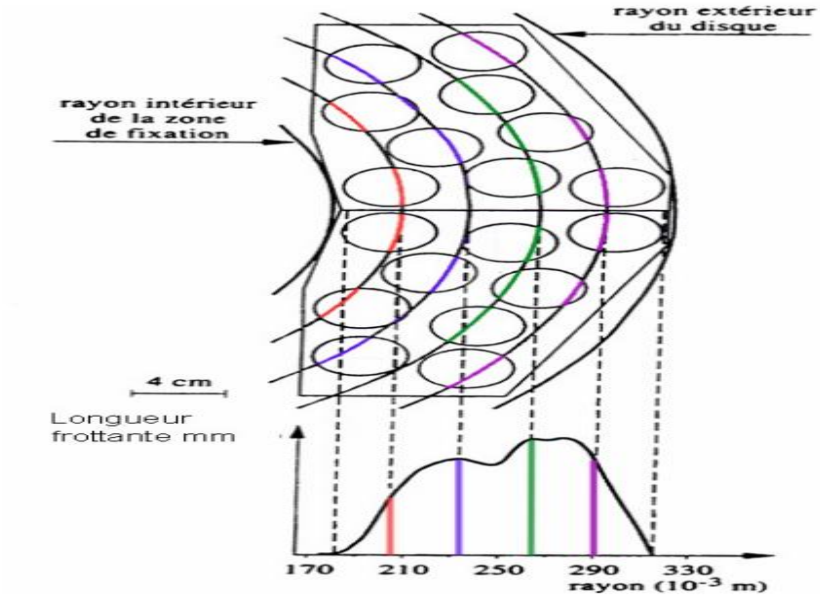


Figure 15. Plot radius vs friction length

Kim et al. [21]

This work focusses on formulation effects of sintered friction materials and made lot of sample brake pads. Then they have done performance test using full inertia dynamometer. This performance test was done at “Poli” Italy. The friction properties of this product was almost identical with the brake pad which is currently used to TGV. And the temperature of brake disc on braking speed 350 km/hr was a little higher.

3.2 Tribology, vibration, wear and microstructure of brake pad composites

Tang et al. [22]

This work focusses on monitoring the vibration and sound responses created by different shape of copper brake pads under dry and wet conditions. The method of fabrication of brake pad was using powder metallurgy. Hardness of the copper brake pad was $HV_{0.5}$ 181 to 223 kg/mm^2.Characterisation was done by scanning electron microscope, energy dispersive X-ray spectroscopy. Customised small-scale dynamometer was used to measure responsiveness of the Copper brake pads with speed and pressure. Triangular block shows highest vibration and sound responses under dry condition. Circular block had shown nil vibrational response and discontinuous responses were shown by hexagonal and triangular blocks under wet conditions. Cracks and wear started with high amplitude vibration.

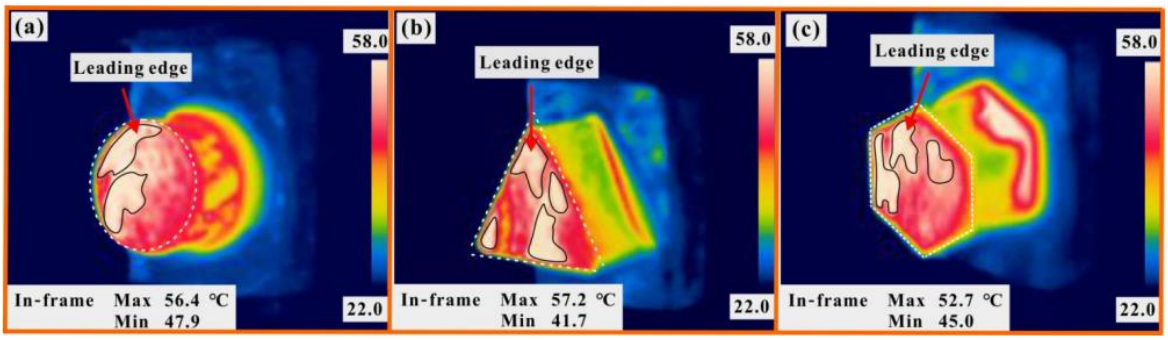


Figure 16. Thermal distributions on block surface at the end of tests for the (a) circular, (b) triangular, and (c) hexagonal blocks.

Xiang et al. [23]

This work revealed the reaction between brake pad and counter disk during which vibration occurs. The method of fabrication of brake pad was using powder metallurgy. Hardness of the copper brake pad was 15-25 HB and counter disk was 342 HB. Finite element analysis (FEA) was done using ABAQUS along with thermal scanning. Customised small-scale dynamometer was used to measure responsiveness of the copper brake pads with speed and pressure. Different vibrational reactions were observed at different rotation speeds of brake disc. At low rotation speeds vibration and sound levels peaks. It was also observed that brake pressure was also not uniformly distributed between brake pad and disk due to which localised stress was observed at edges of the brake pads. FEA confirmed that high frequency noise was created at lower speed Figure 4. Contact inclination angle formed between brake disk and brake pad was also influential factor in effecting pressure distribution.

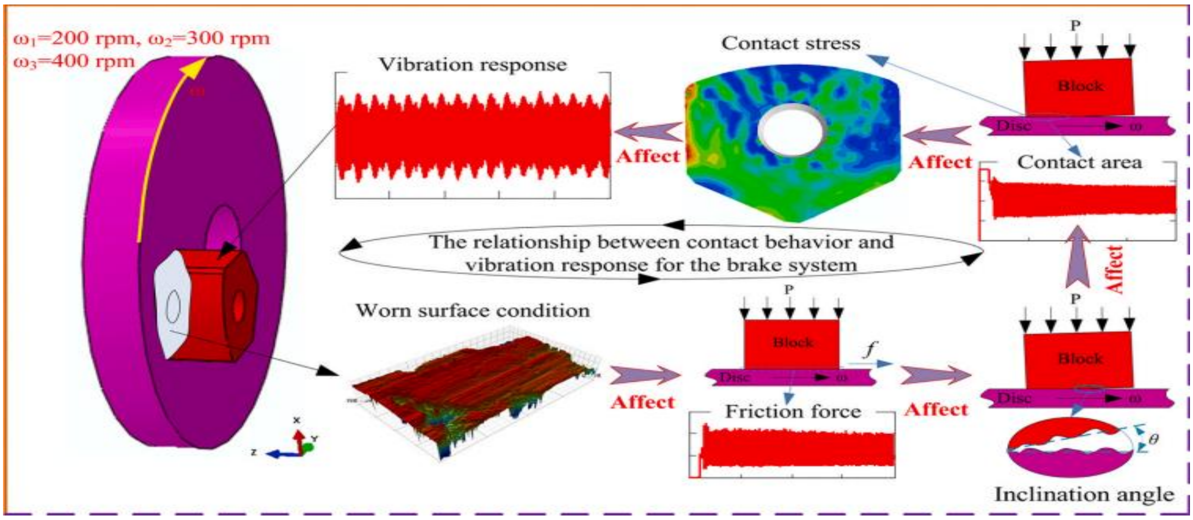


Figure 17. Relationship between contact behaviour and vibration response for the brake pads **[20]**

Desplanques et al. [24]

This work revealed the tribological reaction between brake pad and counter disk during which pressure, speed and stop brake duration act as triplet. In first part experiments was done on reduced and full-scale dynamometer and relation between them was derived using some models of triplets. Similitude rules were also used on the dynamometer. Pin on disc test is done for different triplet conditions. It was observed that pin on disc tribometer was able to reproduce triplet results of full scale tribometer. Stop braking duration was one of the most critical parameters. In second part, more emphasis was on physical phenomena.

Munoz et al. [25]

This work focusses on the study of microstructure Fe-Cu brake pads. The method of fabrication of brake pad was using powder metallurgy. Graphite of small and medium size were used. Hardness of the copper brake pad was as shown in Figure 3. The microstructure directly effects the compressive behaviour. Microcracks appears in the composite after compressive test are completed. The worn surface consists of three layers with top layer rich in carbon. Characterisation was done by scanning electron microscope. Lab scale dynamometer was used to measure responsiveness of the Iron and Copper brake pads with speed and pressure. It was found that copper brake pad was more responsive to bulk behaviour for considering new materials as constituents.

Table 21: Martens hardness in GPa (standard deviation) of the virgin and worn material

Virgin Material	Worn Material		
	Top	Middle	Bottom
0.30(0.21)	0.46(0.31)	0.31(0.18)	0.32(0.20)

Xiao et al. [26]

This work focusses on the study of wear mechanism of Cu brake pads. The method of fabrication of brake pad was using powder metallurgy. Graphite and silicon carbide particles were also used. Hardness of the copper brake pad was as shown in Figure 18. Full scale dynamometer was used for measuring the responsiveness of the brake pad towards speed and pressure. Cracks were seen in the composite brake pad. Tribolayer appears in the composite after brake pad comes in contact with brake disk. Spallation region was also observed on the brake pad surface. Due to abrasive wear grooves were formed on the surface. Characterisation was done by scanning electron microscope, energy dispersive X-ray spectroscopy, XPS analysis. At high speeds the temperature of the surface rises due to which graphite disappears leaving pores. Cupric oxide and ferric oxide were formed when oxygen comes in contact with brake pad at high temperature Figure 5. During this period the oxide based tribolayer was created which has high coefficient of friction (0.31) and low wear in comparison to the base layer.

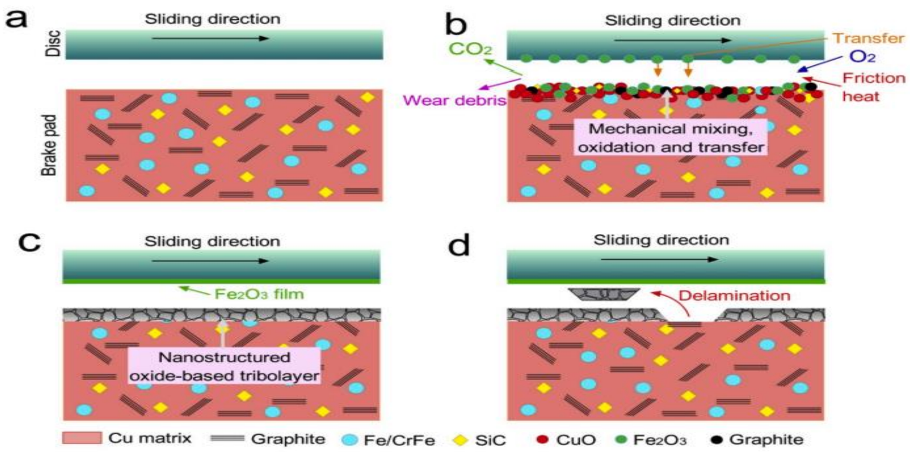


Figure 18. Schematic diagram showing the wear mechanism of the Cu-based brake pad braking at high speed **[18]**

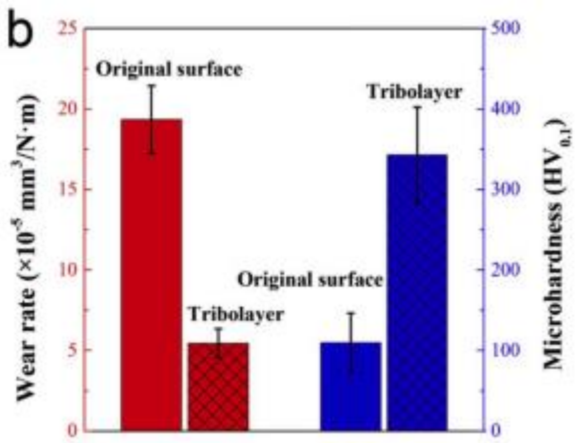


Figure 19. Wear rate and microhardness

Neis et al. [27]

In this paper investigation were done on the structures existing on the surface of brake pads and classified those structures as (i) deformable and non-deformable primary plateaus, (ii) secondary contact plateaus with and without aid from the pad's structural components (primary plateaus), and (ii) the "elastic highlands.". The lower friction forces were generated without the aid of structural components on the deformed primary and secondary plateaus, resulting in a lower friction coefficient.

Lee et al. [28]

This work focusses on the study of structures formed when brake pad mates with brake disk. The method of fabrication of brake pad was using powder metallurgy. Two samples of brake pads are fabricated one low metallic and other non asbestos. Copper and brass along with phenolic resin are used. Hardness of the plateaus formed out of metal fibres was about 79-119 HV. Laboratory scale dynamometer was used for measuring the responsiveness of the brake pad towards speed and pressure. Deformed primary plateaus and Type II secondary plateaus were formed in non-asbestos brake pad. Non-Deformed primary plateaus and Type I secondary plateaus were formed in low metallic brake pad.

Fan et al. [29]

In this paper wear mechanism was due to abrasion and adhesive wear in C/SiC brakes. The method of fabrication of brake pad was using powder metallurgy. Silicon carbide was found responsible for abrasion. Silicon was also found responsible for adhesive wear causing deviation in coefficient of friction**.**

Chen et al. [30]

This work focusses on the fabrication of copper brake pads consisting of both graphite and hexagonal boron nitride (0-10%). The method of fabrication of brake pad was using powder metallurgy. Tin, aluminium and iron were also added Table. Micro Hardness of the samples was as shown in Table 22. Samples containing high amount of graphite have shown low wear rates while samples containing higher amount of Boron carbide show higher friction coefficients. Characterisation was done using Scanning electron microscope and X-ray diffraction technique. Block on ring tester was used for measuring the responsiveness of the brake pad towards speed and pressure.

Table 22 Micro-hardness of Cu- based friction composites

	G0	G2	G5	G8	G10
Microhardness value	110	106	122	103	114

Zhou et al. [31]

This work focusses on studying friction and wear maps of copper brake pads consisted of iron (0-20 %). The method of fabrication of brake pad was using powder metallurgy. Graphite and iron were also added Table 23. Brinell Hardness of the samples was as shown in Figure 7. Samples containing high amount of iron (>15%) have shown delamination wear. Medium content iron (5-15%) shown oxidation, coefficient of friction declines slowly and low wear rate. Low amount of iron (<5%) shown adhesion wear. Characterisation was done using scanning electron microscope.

Table 23: Composition of Cu-MMCs (vol. %).

Sample No.	Cu	Graphite	Fe
1#-6#	60	40	0
7#-12#	55	40	5
13#-17#	50	40	10
18#-22#	45	40	15
23#-28#	40	40	20

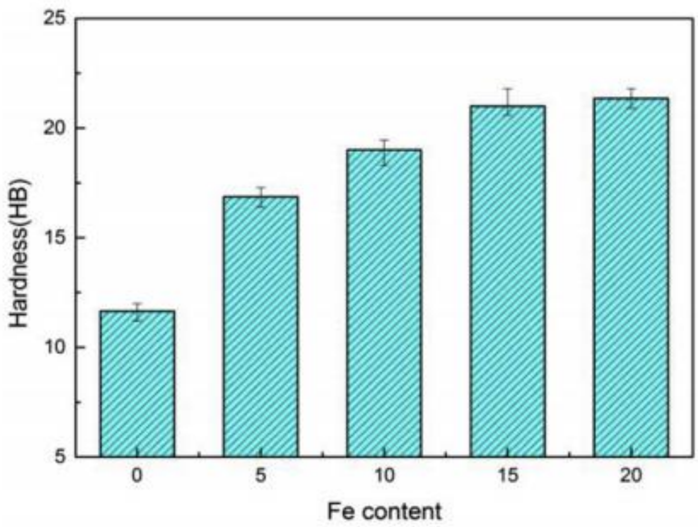


Figure 20. Brinell hardness values of friction materials with different Fe contents

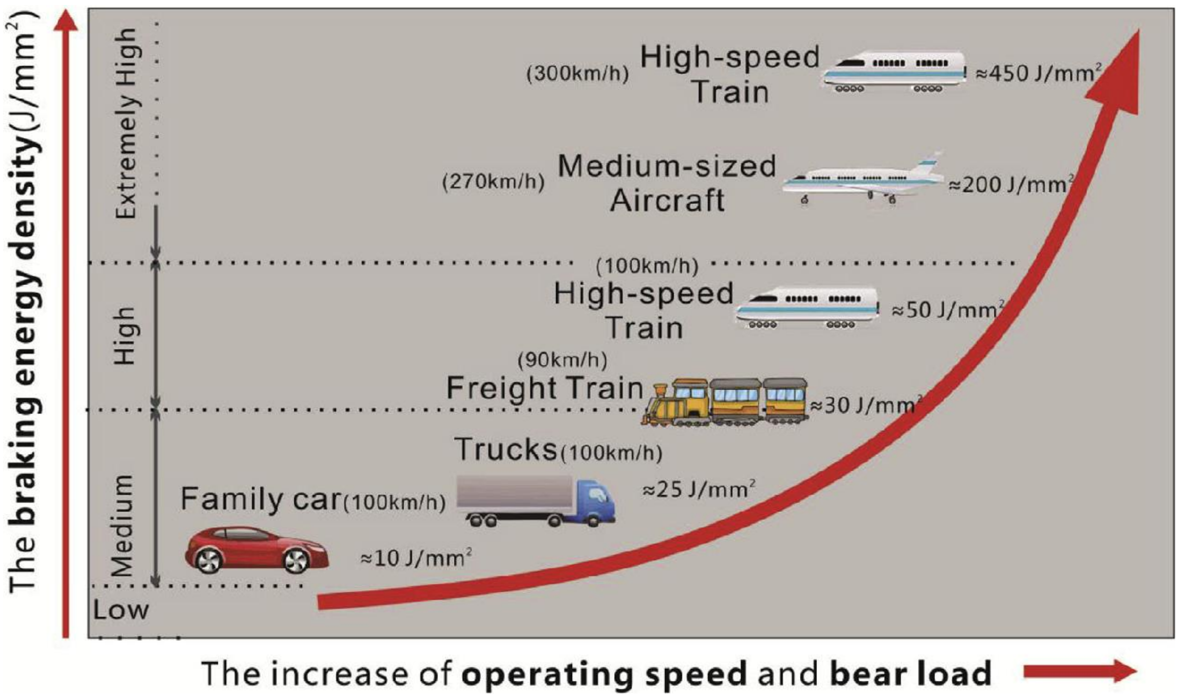


Figure 21. The braking energy density of different application under normal operation condition.

Wang et al. [32]

This work focuses on the effect of brake pad texturing on frictional characteristics and sound level. The method of fabrication of brake pad was using powder metallurgy. Characterisation was done by scanning electron microscope. Pad on disc tribometer was used to measure the responsiveness of the brake pads with speed and pressure. Six grooves were straight cut, having a fixed length and width. Two groove configurations were used one inclined at 45° and the other at 90°. The former one 45° groove configuration performed well in reducing noise, collecting wear debris and improving pressure distribution between brake pad and brake disc.

Benseddiq et al. [33]

This work focuses on enhancing the design of brake pad used in railway using a thermomechanical algorithm. The matrix was reinforced by fibres and the brake pad was made in three layers. A study of pressure distribution was also done, which was critical for temperature observation. It was found that grooves in the brake pad help in improving pressure distribution as well as collecting wear debris during the mating of the brake pad and disk. In algorithm first contact surface were taken into consideration, then calculations were done for heat transfer then a wear study was done. Finally contact surface study was done again take into account of variation.

Wang et al [34]

This work focuses on fabricating self-lubricating copper composites consisting of tungsten disulfide. The method of fabrication was using powder metallurgy via hot pressing and sintering techniques. Micro hardness was measured by Vickers indentation, shown in Figure 9. Characterisation was done using a Scanning electron microscope and X-ray diffraction technique. The coefficient of friction of the composite with 20% tungsten disulfide remains non-deviating for a longer duration.

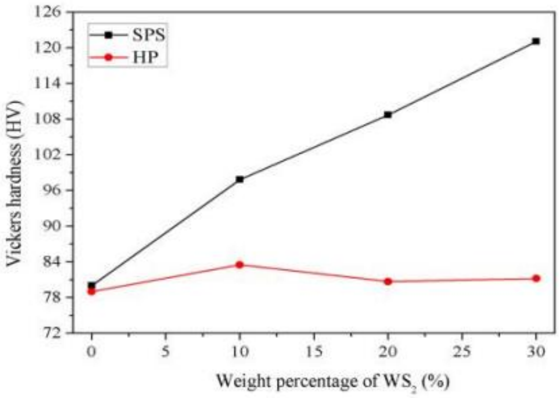


Figure 22. Vickers hardness of Cu/WS_2 composites fabricated by SPS and HP.

Jin et al. [35]

This work focuses on studying the effect of adding enhanced graphite in friction materials. The method of fabrication was resin-based. It was found that the composite containing enhanced graphite coefficient of friction was non-deviating during fade while natural graphite COF was better in recovery Figure 10. Wear rate was also low for enhanced graphite.

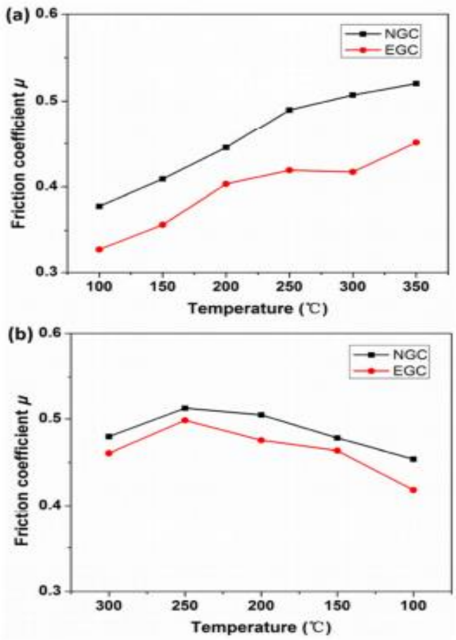


Figure 23. Coefficients of friction for: (a) fade process and (b) recovery process.

Rodrigues et al. [36]

This work focuses on the influence of the addition of copper on the steel pad against the steel disk. The method of fabrication of the brake pad was using powder metallurgy. Hardness of the steel pin was 419+_5 HV. Graphite and magnetite were also added. Characterisation was done using a Scanning electron microscope, focused ion beam microscopies. It was found that copper particles were able to increase the coefficient of friction, form a tribolayer. A pin-on disc tribometer was used to measure frictional properties.

Zhang et al. [37]

This work focuses on studying the effect of braking speed and pressure on the frictional characteristics of copper brake pads. The method of fabrication of the brake pad was using powder metallurgy. Iron and tin were also added. Hardness of the disk was 37 HRC. Characterisation was done using a Scanning electron microscope and X-ray diffraction techniques. It was found that at slow speeds the coefficient of friction, temperature increases, along with pressure and adhesive wear takes place. During high speeds the coefficient of friction declines and oxidation wear takes place. Lab lab-scale test bench was used to measure frictional properties.

Qian et al. [38]

This work focuses on investigating the influence of vibration and wear on the contact sliding surface. Contact plateaus were created by uneven wear. Non-uniform contact pressure between sliding surfaces results in uneven wear and unstable vibration. A study of these phenomena was done by a small-scale tribometer. Sensors were being fitted to measure unwanted vibration. The finite element method was also used for this purpose. It was also found that a rise in the coefficient of friction was accompanied by vibrations.

Ferrer et al. [39]

This work focuses on the study of the friction and wear characteristics of alloy brake pads. The method of fabrication was powder metallurgy. Iron, chromium and tin were also added. Hardness of the alloy brake pads was 39 HB. Pin-on disc test was done to measure the coefficient of friction and wear at different pressures and speeds. It was found that the coefficient of friction of the sintered alloy brake has a constant and 80% more higher friction coefficient compared to the cast iron shoe. At higher speeds coefficient of friction and wear of the alloy brake pad increase. Thermal analysis of the brake pad was also done.

Zhang et al. [40]

This work focuses on the fabrication of copper composite brake pads and their fading during heavy loads. The method of fabrication was powder metallurgy. Iron, graphite, tin, chromium and silicon dioxide were also added in Table 10. Hardness of the brake disc was 38-44 HRC. A reduced-scale tribometer was used to measure the coefficient of friction and wear at different pressures and speeds. The braking protocol was made in such a way to simulate emergency braking conditions. Characterisation was done using a scanning electron microscope, energy dispersive X-ray spectroscopy and X-ray diffraction technique. It was found that as braking time increased, fading started to begin. The reason behind fading was due to softening of the copper matrix due to high braking time. Two types of tribofilms were formed first with the oxidation of iron particles and second after break of first one when copper matrix softens giving rise to a tribofilm containing alternative iron copper layers. Copper acts in dual role at low temperature, it increases the coefficient and high temperature it acts as a lubricant, reducing the friction coefficient. It was observed from the Figure, a multi-layered friction layer composed of alternating Cu- and Fe-rich layers was formed. The metal oxide formed on the friction surface decreases and balances the friction coefficient in addition to improving wear resistance because it reduces the chances of metal-to-metal contact between the brake pads and brake disc. As above, the point that the performance of the friction coefficient is closely related to the friction layer has become a consensus.

Table 24: Chemical compositions of Cu-based friction materials (wt%)

Cu	Fe	C	SiO_2	Cr	CrFe	Sn
54	26	10	2	3	4	1

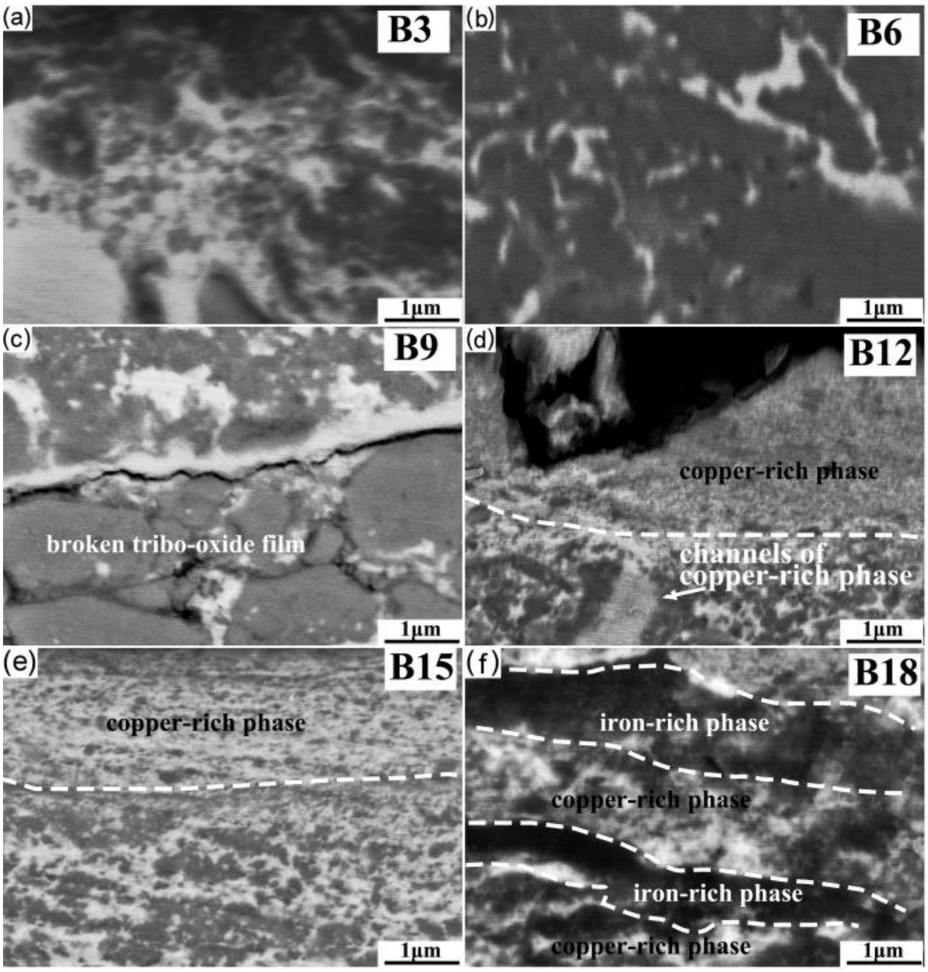


Figure 24. Corresponding magnified cross-sectional BSE images of rectangular areas

Papinniemi et al. [41]

This work focuses on the study of brake squeal. Brake squeal produces undesirable noises that cause discomfort to passengers. The efforts to break the squeal were studied, including analytical, numerical, and experimental methods. Finite element analysis was also used in the study.

Öztürk et al. [42]

This work focuses on the study of friction and wear of composites reinforced by various kind of fibres. Various fibres include E-Glass, steel wool, ceramic, and rockwool. The method used for fabrication was by using phenolic resin. Characterisation was done by using a Scanning electron microscope and, X-Ray diffraction technique. Hardness of the samples containing fibres was as shown in Table 25. It was observed that the coefficient of friction and wear was peaks for steel wool and E-glass.

Table 25: Properties of composites

Properties	RF30	CF30	GF30	SF30
Density (g/cm^3)	2.40	2.45	2.38	3.72
Rockwell hardness (M scale)	94	103	92	99
Flexural strength (MPa)	74	72	113	65
Shear strength (MPa)	26.4	29.8	24.2	23.4
Compressive strength (MPa)	211	205	193	190
Thermal conductivity (W/mK)	1.15	1.07	1.14	2.18

Alturbeh et al. [43]

This work focuses on the study of simulation software, which helps in evaluating brake performance of electric multiple units. The software tool calculates the various parameters that are necessary for train operation, like speed, traction forces, distance and time required for braking. It helps to monitor the different rolling stock parameters required for its efficient running.

Lee et al. [44]

This work focuses on the study of aerodynamic brakes for high-speed trains. Computational fluid dynamics analysis was being carried out in order to simulate the brake performance. Various drag situations were simulated at different speeds and coefficients.

Wang et al. [45]

This work focuses on the study of brake callipers of high-speed rolling stock operating in snowy conditions. It was observed that under snowy conditions, the snow particles get stuck in the bottom region of the rolling stock. The rear portion is affected more than the front portion. To avoid snow particles sticking into brake callipers, snow shields of different shapes were mounted and tested using numerical methods. After that, it was observed that cambered snow shields performed better than triangular and trapezoidal ones.

Olofsson et al. [46]

This work focusses on studying the effect of snow on train brakes operation. Four composite blocks have been made and tested on pin on disk setup. Composites with high metallic content tend to show high friction coefficient. Different shapes were tried one in which two tracks were milled on the composite surface.

Abbasi et al. [47]

This work focuses on studying the effect of particulate emissions from Railroad traffic. Toxic contaminants that were harmful to nature were identified, and their particulates were being measured. PM2.5 and PM10 were the particulate size levels on which emission levels were measured. Legislation for preventing the emission levels was also discussed. Metals like aluminium, copper, cobalt etc. were also selected in the study of emissions.

Li et al. [48]

This work focuses on the fabrication of C/C-SiC brake pads. The method of fabrication was by chemical vapour infiltration. A full-scale dynamometer was used to test the friction coefficients and wear at different speeds and pressures. It was observed that the brake pad has good friction coefficients and wear resistance. It has only one limitation of high cost.

Xiao et al. [49]

This work focuses on the review of friction materials. Friction materials were classified according to matrix material and material source. Further, in matrix material, frictional material was classified into metallic, semi-metallic and non-metallic matrix. Types of tribofilms formed were also discussed, along with plateaus formed on the contacting surface. The impact of temperature on tribology was also studied. The effect of braking pressure and speeds was also considered in the study.

Krishnan et al. [50]

This work focuses on the fabrication of aluminium and iron. The method of fabrication was using phenolic resins. The objective of the paper was to replace copper in automobile brakes due to its toxic nature. Though copper is good in terms of thermal conductivity, friction coefficients it requires two or more ingredients to replace it completely. Mechanomade was tested using a Chase-type testing machine for evaluating its tribological properties. Hardness of the aluminium-iron alloy was found to be good, and it also showed good frictional properties.

Campos et al. [51]

This work focuses on the study of high-speed railway (HSR) projects in various countries. It also includes the various models adopted in different countries for operating the HSR, like exclusive exploitation, mixed high speed, mixed conventional, and fully mixed. It also studies the various costs of maintaining and running the high-speed railways in countries like France, Germany, Italy, and Spain. This paper throws light on the economic aspects of high-speed railway.

Lazim et al. [52]

This work focuses on investigating the sound created when we introduce silica particles between the brake pad and disc. Three sizes of silica particles were introduced between the mating surfaces. Different silica particle creates different types of secondary plateaus. Small-sized silica particles in the range of 100 to 200um create small flat areas which produce a high friction coefficient and unpleasant sound in comparison with large particles (200 to 400 um).

Zhao et al. [53]

This work focuses on investigating the tribology of wet clutches at high temperature. The method of fabrication was powder metallurgy. Iron and carbon were also added. Pin-on disc test was done to measure the friction coefficients and wear at different speeds and temperatures. It was observed that the friction coefficient rises when the temperature rises from 120 °C to 270 °C and decreases when the temperature rises further to 420 °C. Similarly, it was observed that wear declines initially slowly when 120 °C to 270 °C and declines faster when the temperature reaches to 420 °C.

Jang et al. [54]

This work focuses on the fabrication of a brake pad with different metal fibres, mating them with two brake discs. The method of fabrication was by using phenolic resin. The metal fibres used were copper, aluminium and steel. Hardness of the brake material was 84+-5 HRs. A laboratory-sized dynamometer was used to measure the friction and wear at different speeds and pressures. It was found that copper fibres performed well on both Aluminium disks, cast iron disks while steel fibres generated the highest wear.

Österle et al. [55]

This work focuses on the study of lubricants used in brake pads. It was observed that the use of single lubrication was not appropriate, and multiple lubricants must be used to get better results. A study of tribofilms was also done, which were formed between brakepad and brakedisk using different characterisation methods like scanning electron microscope, X-ray diffraction, etc. Various oxides were found to form in the tribofilm during testing on a dynamometer.

Gbadeyan et al. [56]

This work focuses on the study of the friction and wear of nano nano-scale composite brake pad. The method of fabrication was by using epoxy resins. Carbon fibre and graphite were also used. Characterisation was done using a scanning electron microscope. A laboratory-sized brake dynamometer was used to measure friction and wear at different speeds and pressures. It was observed that with an increase in carbon percentage, the coefficient of friction also increases. It was also found that in nanoscale composites, with increasing speed, the wear rate declines.

Wasilewski et al. [57]

This work focuses on studying the thermal aspects of the brake pad and brake disk. It focuses on considering thermal aspects during the design phase rather than performing tests on a full-scale dynamometer. This paper also reviews the various shapes and sizes of brake pads that can be used to prevent cracks. It also considers that friction coefficients were not constant during the whole span of braking and it depend on various factors like temperature and speed.

Asif et al. [58]

This work focuses on the fabrication of aluminium-based brake pads and studying their wear characteristics. The method of fabrication was by using Hot powder preform forging. Hardness of the brake pads was 70+-5BHN. Zinc, graphite and silicon carbide were also added to Table 26. Pin-on disc test was conducted to measure friction coefficients and wear at different speeds and pressures. Wear and friction coefficients were found satisfactory.

Table 26: Chemistry of aluminium-based brake pads along with density and hardness

Materials	Al (100μm) (wt.%)	Zn (75μm) (wt.%)	Graphite-fine-45 μm (wt.%)	SiC-400μm Sb_2S_3-40μm $BaSO_4$-40μm (wt.%)	Density gm/cc	Hardness BHN
ALM-01	78.35	3	9.54	SiC(coarse) -8.45, $BaSO_4$-3, Sb_2S_3-2	2.94	74
ALM-02	76.01	3	7.54	SiC(coarse) -6.45, $BaSO_4$-3, Sb_2S_3-2	2.86	69
ALM-03	77	-	9.5	SiC(coarse) -8.5, $BaSO_4$-3, Sb_2S_3-2	3.02	70
Backing plate	80	-	-	SiC-20	-	-

Table 27: Pin on Disc Wear test at a speed of 9m/sec., 5kg load. Area of the pin = 49mm^2

Materials	Cumulative wear (gm)	COF (μ)	Temp. (°C)	Sound Level (db)
ALM01	1.8	0.395	106	28.5
ALM02	1.98	0.515	114	25.5
ALM03	1.7	0.375	123	25

Ponnambalam et al. [59]

This work focuses on the fabrication of copper brake pads. The method of fabrication was by using powder metallurgy. The hardness of the brake pads was shown in the Table. Silicon carbide and Fly ash were used as reinforcement. Pin-on disc test was conducted to measure friction coefficients and wear at different speeds and pressures. Grey relational analysis was also used to select the best parameters.

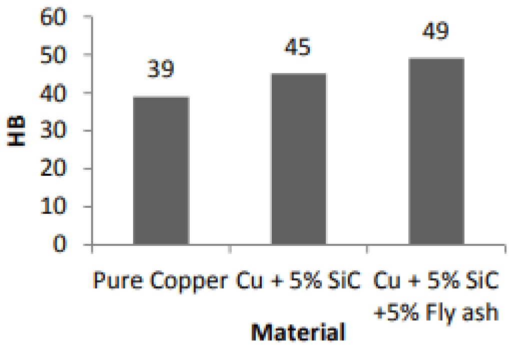


Figure 25. Brinell Hardness Test Results

Zhou et al. [60]

This work focuses on the study of different generations of high-speed railway(HSR) developed in different countries. The study starts from HSR developments in Japan, then to France and Germany. Finally, the study moves to HSR developments in China, where trains run above 350kmph.

Blau et al. [61]

This work focuses on the influence of introducing water on the tribology of truck brakes. It was found that with water spray, the frictional coefficients decline.

Rodrigues et al. [62]

This work focuses on the study of tribofilm when copper was added. Graphite was also added. Pin-on disc test was carried out to measure the friction coefficient at different speeds and pressures. Copper introduced at environmental temperature showed a higher friction coefficient than introduction done at 400 °C. It was observed that a tribofilm consisting of magnetite was formed with a small amount of copper. Characterisation was done by using TEM, energy dispersive spectroscopy.

Bao et al. [63]

This work focuses on the study of the tribology of brake pads used in mine hoisting. The method of fabrication was by using phenolic resin. Carbon, Silica and Manganese were also added. A pad on a disc tribometer was used. Hardness of the brake pad was 287 N/mm^2.Characterisation was done by using a scanning electron microscope. It was observed that with increasing initial velocity, the friction coefficient declines, then increases in between and then declines further. A study of tribofilms and their influence on the declining friction coefficient has been done in detail.

Table 28 Compositions of the 16Mn brake disc (weight percentage)

C	Si	Mn	Cr	P	S	Ni	Cu	Fe
0.15	0.50	1.60	0.30	0.03	0.03	0.30	0.25	Bal.

Sharma et al. [64]

This work focuses on the study of adding copper nanoparticles to a brake pad. The method of fabrication was by using phenolic resin. Barite was added to one of the samples. Nano powder was added in 2% wt to the parent composition. It was observed that the addition of nanoparticles improves their properties like hardness, thermal conductivity, fade resistance, etc. Characterisation was done by using a scanning electron microscope. It was also found that by the introduction of nanoparticles, a good tribo film was formed, which reduces wear.

Mahale et al. [65]

This work focuses on the study of introducing stainless steel swarf(0-20%wt) in a brake pad. The method of fabrication was by using phenolic resin. Alumina, Potassium titanate were also added to the samples. Hardness of the samples was as shown in the Table. Characterisation was done by scanning electron microscope, energy dispersive X-ray spectroscopy. It was observed that the addition of stainless steel swarf (SSS) improves its properties like hardness, thermal conductivity, fade resistance, etc. and improves the friction coefficient. It was also found that by introduction of 5% wt SSS reduces wear to a great extent.

Table 29: Results of physical, chemical and mechanical characterisation

Properties	S_0	S_5	S_{10}	S_{15}	S_{20}	C_{10}
Density (g/cc)	1.81	1.99	2.07	2.19	2.27	2.31
Oil porosity (%) (JIS D 4418)	1.21	1.17	1.12	1.10	1.04	0.79
Water porosity (%) (JIS D 4418)	1.73	1.57	1.52	1.38	1.36	1.37
Acetone extraction (%) (ASTM D 494)	0.18	0.12	0.11	0.16	0.13	0.11
Thermal conductivity (W/mK)	1.09	1.52	1.55	1.77	1.80	1.83
Hardness (HRS) (ASTM D 785)	95	96	97	98	100	101

Kumar et al. [66]

This work focuses on the study of the friction and wear of brake pad composites consisting of metals. Three samples were fabricated: one with copper, a second with brass and a third with iron. Rockwell hardness of the composites was in the range of 85+-10(S-scale). Characterisation was done using a scanning electron microscope. A reduced-scale prototype tribometer was fabricated to measure the friction and wear at different speeds and pressures. It was observed that with the introduction of metals in the samples, the hardness, thermal conductivity, fade resistance etc., improved significantly. Copper-based composites performed satisfactorily in the three samples.

Fan et al. [67]

This work focuses on the study of the friction and wear of C/SiC brake pads composites. The method of fabrication of the brake pad was by powder metallurgy. Adhesive wear was a prominent wear mechanism found in this brake type. Silicon plays a key role in determining the wear type.

Gilardi et al. [68]

This work focuses on the influence of graphite type on brake pad squeal and thermal conductivity. It was found that the TIMREX graphite type not only reduces sound but also an effective damper. It was also found that the T-type graphite enhances the thermal conductivity.

Khursheed et al. [69]

This work focuses on the influence of copper on aluminium. The method of fabrication of the brake pad was by casting. Hardness of the sample peaks with the highest content of copper. Chromium, Manganese and Zinc were also added. It was observed that the sample containing 8% copper has the highest ultimate tensile strength.

Deng et al. [70]

This work focusses on the study of friction and wear of carbon/carbon composites. The method of fabrication of brake pad was by isothermal chemical vapor infiltration. It was observed that with rise in brake pressure and brake speed friction coefficient declines and with rise in speed wear increases. Double layer rough laminar and pyro carbon texture have more non deviating friction.

Kang et al. [71]

This work focusses on the fabrication of copper and iron brake pads. The method of fabrication was by hot pressing method. Characterisation was done using scanning electron microscopes and energy dispersive spectroscopy. It was found that copper brake pads performed well at low loads and iron brake pads performed well at high loads. Tribolayer formed in iron brake pads was more stable than copper brake pads in which cracks were seen.

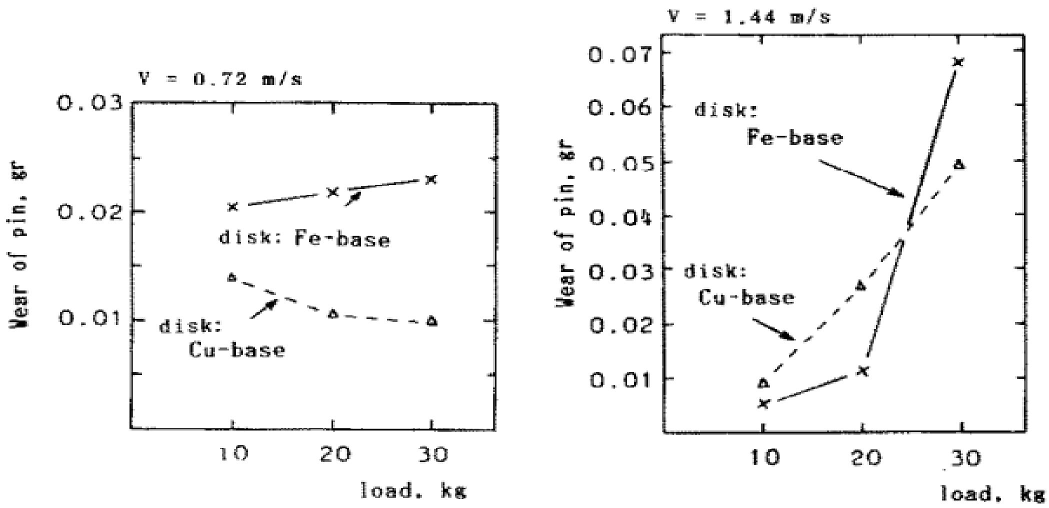


Figure 24. Brake pad composites load vs wear of pin

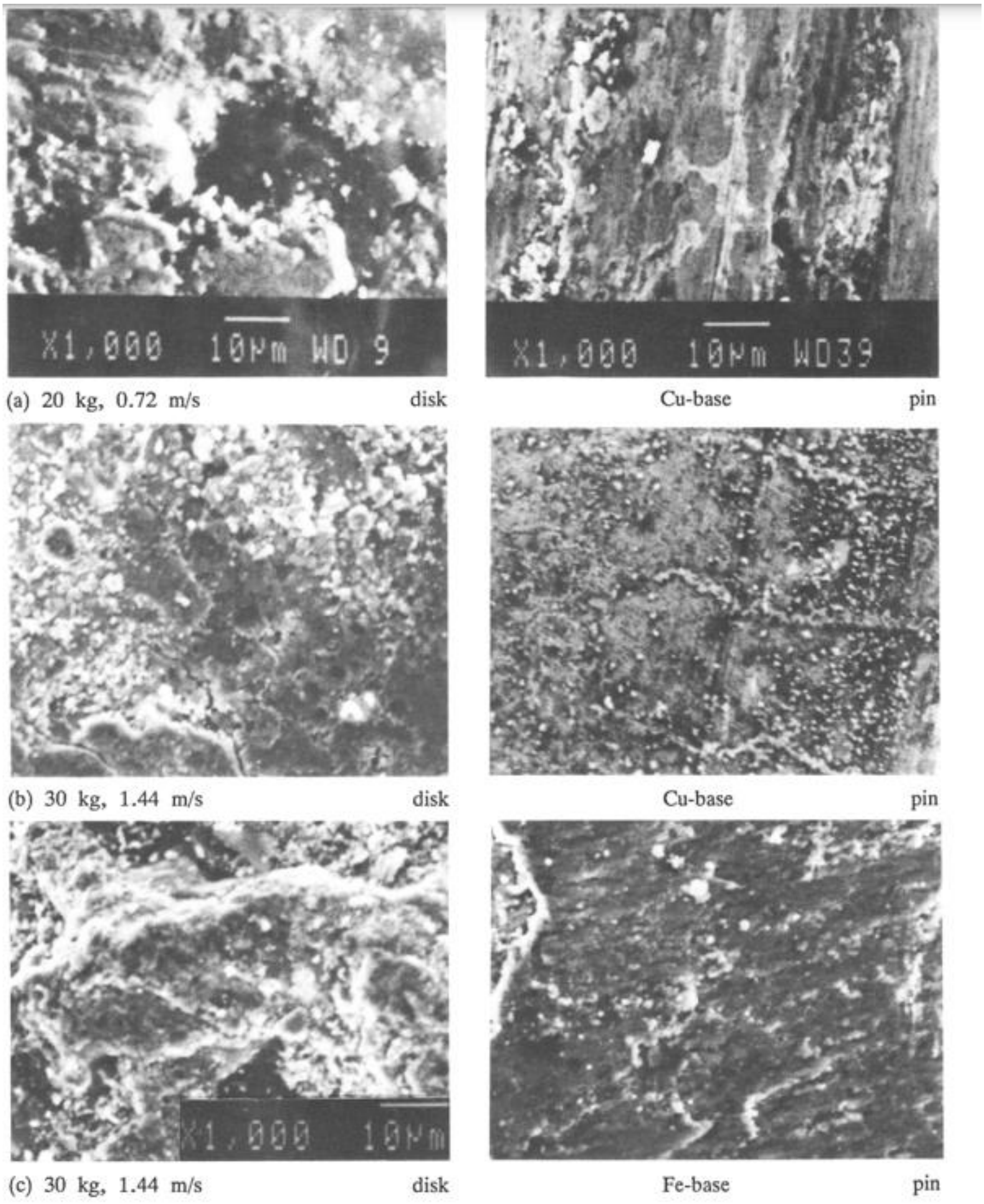


Figure 26. SEM images of the worn surface.

Wang et al. [72]

This work focusses on the study of wear in the train brake disk. It was observed that due to braking a large amount of heat was generated due to which checks and cracks were formed on the brake disk. Due to cracks and checks roughness of the brake disc increases.

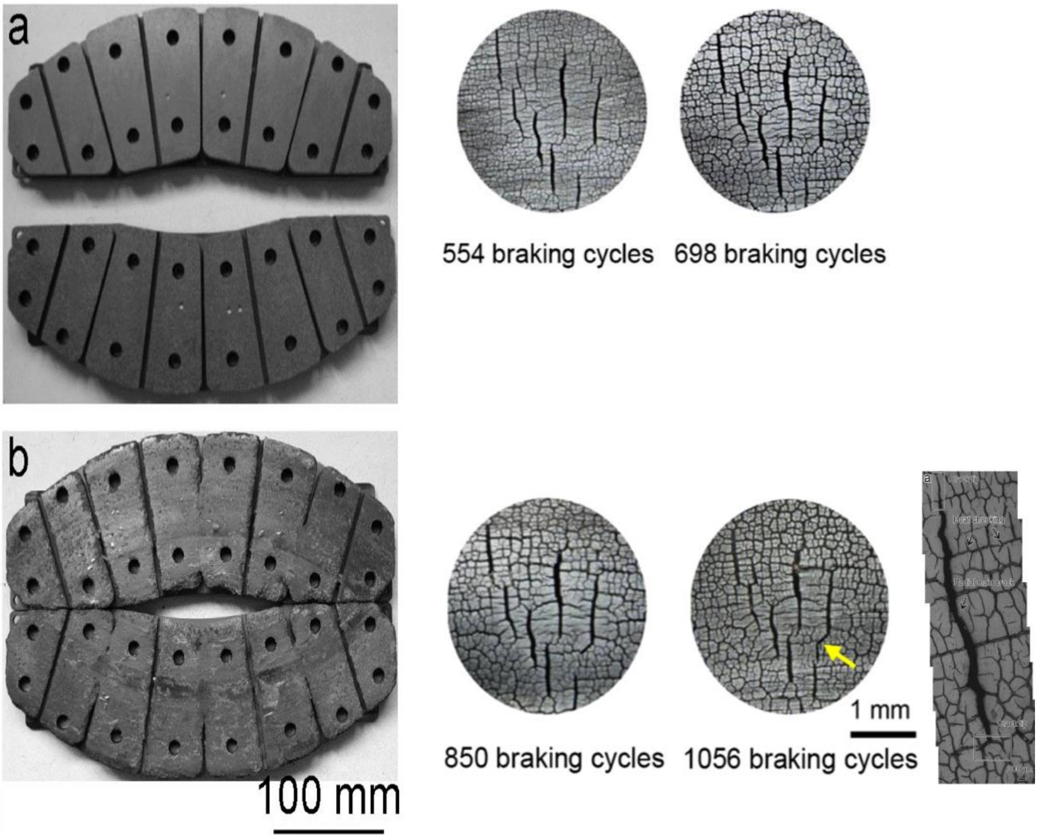


Figure 27. Worn brake pad full scale.

Gyimah et al. [73]

This work focuses on the fabrication of copper brake pads consisting of silicon dioxide and investigates the effect of sintering temperature on mechanical properties. The method of fabrication was powder metallurgy. Iron, Graphite, Tin and Molybdenum disulfide were also added. Hardness of the composite tends to increase with sintering temperature Figure 11. Characterisation was done using a scanning electron microscope and an optical microscope. Pad on disk tribometer was used to measure the friction coefficient and wear. It was found that at high sintering temperatures friction coefficient increased while wear decreased.

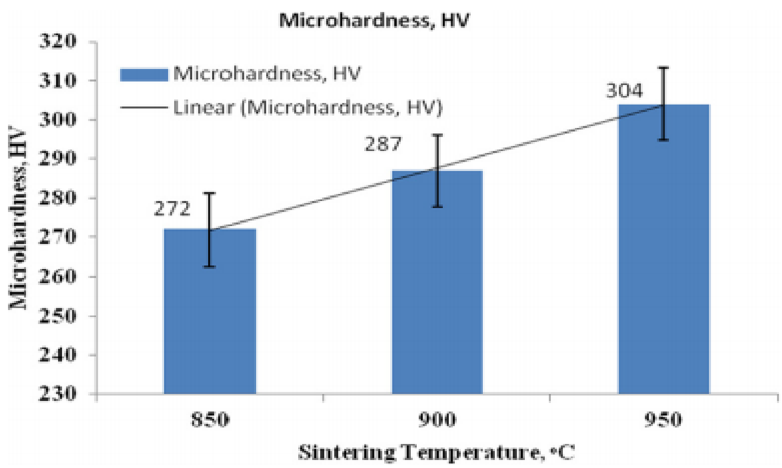


Figure 28. Relationship between hardness and sintering temperature.

Hija et al. [74]

This work focuses on the fabrication of C/C SiC brake pads for use in elevators. The method of fabrication was by using liquid silicon infiltration. A full-scale dynamometer was used to measure frictional coefficients and wear. It was observed that the composite sample showed high friction coefficients, low wear and enough mechanical strength.

Kovalchenko et al. [75]

This work focuses on the study of the friction and wear of copper composites. The method used for fabrication was powder metallurgy. Molybdenum disulfide (0-15wt%) and molybdenum diselenide (0-15wt% %) were also added. Hardness of the samples as shown in Table 29. Pin-on-disk test was used to measure frictional coefficients and wear at different speeds and pressures. The characterisation was done using a scanning electron microscope, energy dispersive spectrometer, and X-ray diffraction. The solid lubricants incorporated control rubbing and damage to the surface. Adhesion wear took place between the surface. Lubrication works above 5wt% concentrations.

Table 30: The initial composition of the powder before preparation of the specimen, specimen porosity and Rockwell hardness

Initial composition of the powder	Porosity (%)	Rockwell hardness, Scale F
Cu + 1 wt% MoS_2	3.0–4.5	51.4–62.2
Cu + 5 wt% MoS_2	4.5–6.0	73.3–76.3
Cu + 10 wt% MoS_2	8.0–9.0	77.1–90.1
Cu + 15 wt% MoS_2	9.0–9.5	77.0–87.6
Cu + 1 wt% $MoSe_2$	8.0–9.0	50.4–53.9
Cu + 5 wt% $MoSe_2$	8.0–9.0	58.8–62.6
Cu + 10 wt% $MoSe_2$	8.0–9.0	67.3–74.9
Cu + 15 wt% $MoSe_2$	6.0–7.0	75.0–79.4

3.3 Brake Pad Formulations Using Industrial Waste

Mohanty et al. [76]

This work focusses on the fabrication of automotive brake pads consisting of coal fly ash. The method of fabrication was using reinforcing phenolic matrix. Three formulations were made using aluminium fibre, Potassium titanate, copper fibre/powder and keeping fly ash as common Table 18. Fly ash was chemically stable, store surplus heat generated at interface, a poor conductor preventing heat flow and most importantly act as abrasive. Characterisation was done using Scanning electron microscope, energy dispersive X-ray spectroscopy. Full scale dynamometer was used to measure frictional characteristics. Formulation containing graphite and copper fibre/powder (by removing extra lubrication) shown encouraging results.

Table 31: Formulations using fly ash

Ingredients used in the composites	
Ingredients	Weight %
Phase I	
Fly Ash	55 to 65
Phenolic Resin	20
Glass Fiber	15 to 25
Aluminium Fiber	0 to 10
Phase II	
Fly Ash	52 to 60
Phenolic Resin	20
Aramid Pulp	3 to 8
Potassium Titanate	4 to 10
Graphite	0 to 10
Phase III	
Fly Ash	50 to 60
MF Phenolic Resin	20
Aramid Pulp	3 to 8
Potassium Titanate	4 to 10
Graphite	5 to 10
Copper Fibre/powder	5 to 10

Table 32: Chemical constituents of the fly ash

Chemical composition	Weight %
SiO_2	31.3
Al_2O_3	10.6
Fe_2O_3	8.3
SO_3	12.8
CaO	20.9
MgO	0.4
Unburnt carbon	12.55
Free moisture	0.11
Water of hydration	0.71
Total Na_2O	0.4
Total K_2O	1.1
Others ($TiO_2 + P_2O_5 + SrO + BaO$)	0.83

Manoharan et al. [77]

This work focusses on the fabrication of automotive brake pads consisting of red mud and iron sulphides (0-10% wt.). The method of fabrication was by reinforcing phenolic resin. Three formulations were made by changing percentage of red mud and iron sulphide from 0 to 10% wt. Aramid pulp and hydrated lime were also added. Red mud behaves like abrasives Table 20 creating contact plateaus while iron sulphide act as lubricative. Combined action of red mud (05% wt.) and iron sulphide (05% wt.) helps in creating a non-fluctuating friction coefficient and low wear during fade and recovery. The wear rate is mainly dependent on the friction layer (tribo film) formation and formation of the film prevents the real contact area between the mating surfaces as a result of wear resistance of friction composites increases. The red mud which acts as an abrasive as the third body during braking leading to plowing action of the surface causing friction performance changes.

Table 33: Elemental Composition of Red Mud

Element	Fe_2O_3	Al_2O_3	TiO_2	CaO	SiO_2	Na_2O
Composition in Wt%	50	21	6	5	15	3

Table 34: Different Formulations with red mud and sulphide powders

Ingredients	**RMC-0 (wt. %)**	**RMC-05 (wt. %)**	**RMC-10 (wt. %)**
	Reinforcement Fibers with additives		
Aramid pulp	9	9	9
Hydrated lime	5	5	5
Ceramic fiber	6	6	6
	Binders with Additives		
Straight phenolic resin	9	9	9
NBR powder	3	3	3
Crumb rubber	4	4	4
Calcium oxide	2	2	2
	Frictional Modifiers		
Synthetic graphite	6	6	6
Red mud	0	5	10

Iron sulphide	10	5	0
	Inert & Functional Fillers		
Synthetic barites	15	15	15
Exfoliated vermiculite	10	10	10
Friction dust	9	9	9
China clay	7	7	7
Tin powder	5	5	5

Balamurugan et al. [78]

This work focusses on the fabrication of copper brake pads consisting of fly ash (0-10% wt) and investigate the effect of process parameters on mechanical properties. The method of fabrication was powder metallurgy. Parameters selected were sintering time, sintering temperature, compaction pressure. Density, hardness, compressive strength rises with compaction pressure, sintering time and sintering temperature. Wear rate decreases with increasing pressure, sintering time and sintering temperature.

Kannan et al. [79]

This work focusses on the fabrication of copper brake pads consisting fly ash. The method of fabrication was liquid sintering. Copper was added in 5%wt with fly ash. Sintering environment was different one in normal air and other in argon environment. Characterisation was done using scanning electron microscope and X-Ray diffraction. It was found that copper brake pad containing fly ash sintered in argon atmosphere was having high hardness and (abrasive) wear rate.

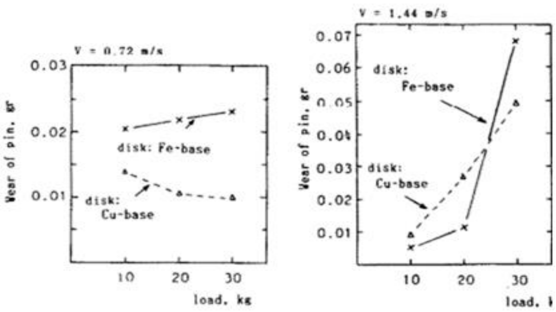


Figure 28. Wear of pin at various loads and speeds.

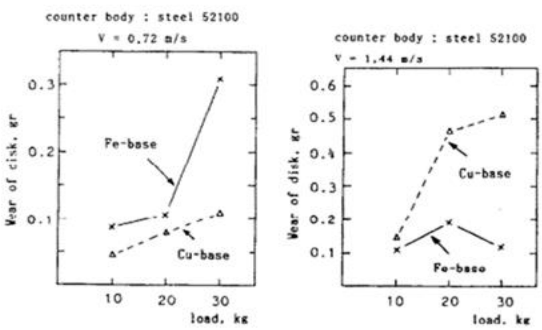


Figure 29. Wear of disks under various sliding conditions.

Shojaei et al. [80]

This work focusses on the fabrication of railroad rubber brake pads consisting of five different ingredients. The method of fabrication was by using phenolic resin. Copper, Brass, Aluminium, Talc and Aluminium oxide were also added. Pad on disc tribometer was used to measure frictional coefficients and wear (Table 22). Brass has highest friction coefficients and low wear.

Table 35: Frictional properties and compressibility of thermally conductive friction materials

Friction material	Coefficient of friction	Specific wear (cm^3)	Elastic compression modulus (N/mm^2)	Volume fraction of SBR in the compound
BM	0.57	0.17	410	0.42
C-Cu-48	0.5	0.18	380	0.48
C-BrII-48	0.48	0.18	440	0.477
C-Al-48	0.42	0.27	800	0.38
C-talc-48	0.22	0.08	920	0.385
C-AlO-48	0.6	1	580	0.406

Ma et al. [81]

This work focusses on the study of friction and wear of cow dung reinforced composites. The method used for fabrication was by using phenolic resin. Samples were also made by reinforcing corn stalk fibres. Characterisation was done by using Scanning electron microscope, X-Ray diffraction technique. Hardness of the samples containing fibres was as shown in Table 35. It was observed that cow dung fibres with 2-4 wt.% exhibited higher friction coefficients and with 6 wt.% (CDF) exhibited better wear resistance.

Table 36: Physio-mechanical characteristics of the composites

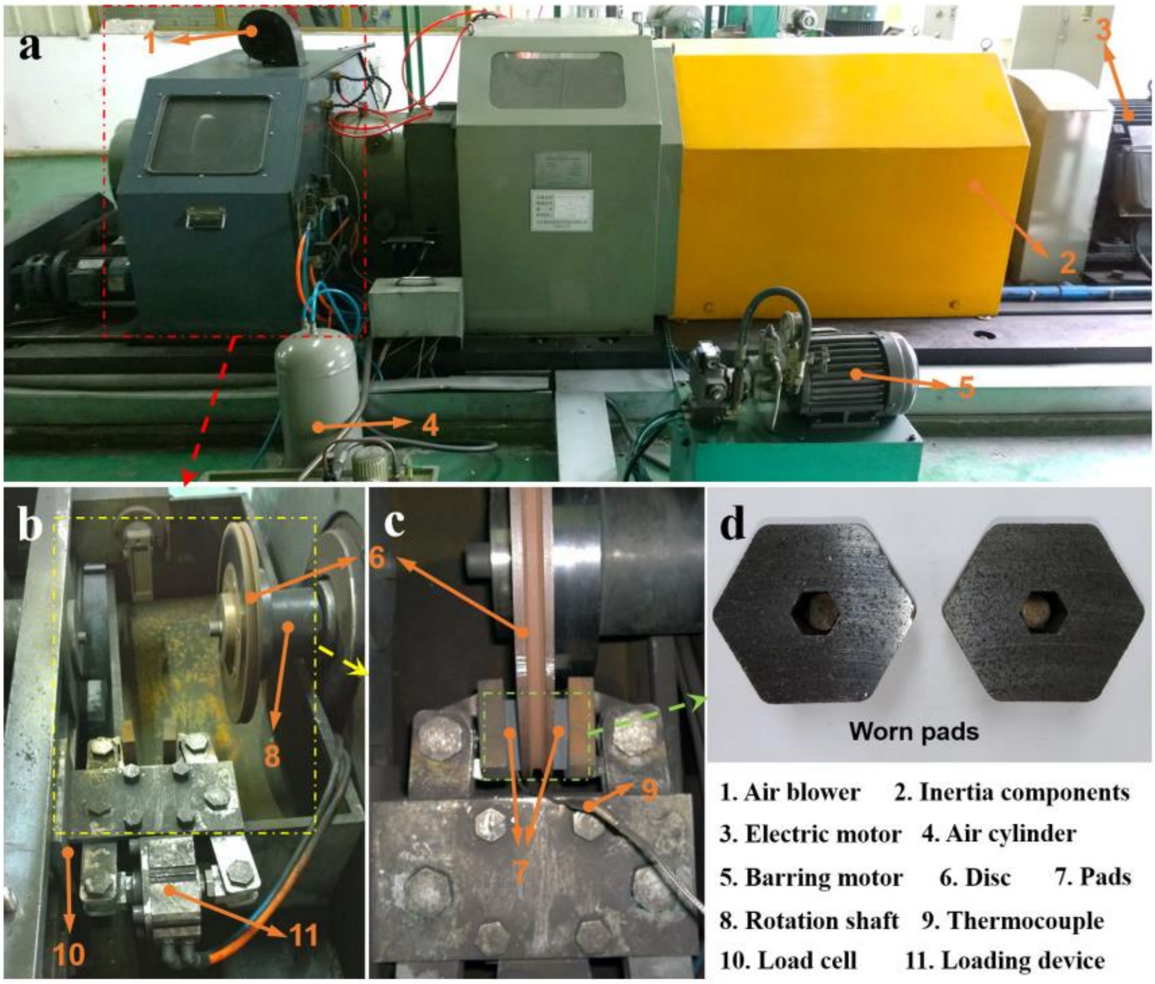
Samples	Density ($g{\cdot}cm^{-3}$)	Porosity (%)	Hardness (HRR)	Impact strength (MPa)
Ref	2.33	6.43	103.6	0.461
FCD-2	2.22	8.16	101.0	0.442
FCD-4	2.17	9.58	98.2	0.497
FCD-6	2.14	10.95	96.3	0.481
FCD-8	2.09	12.47	94.7	0.436
FCS-2	2.25	7.46	101.4	0.424
FCS-4	2.21	8.73	98.9	0.486
FCS-6	2.19	10.04	97.2	0.473
FCS-8	2.13	11.68	95.8	0.422

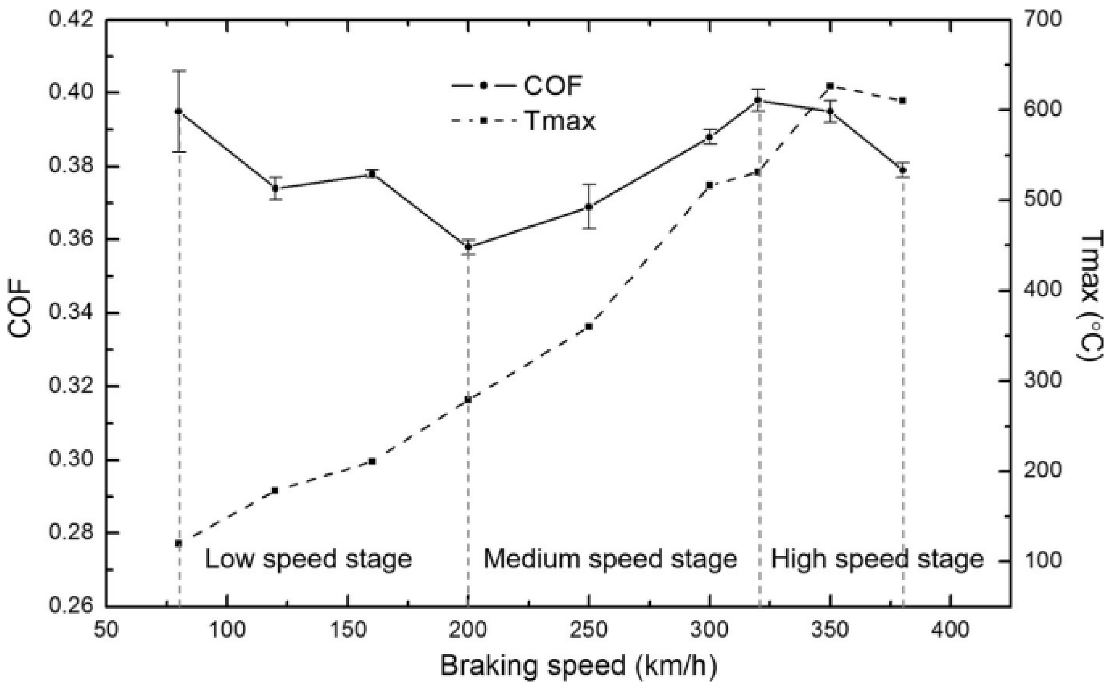
Peng et al. [82]

This work investigates pad on disk test performed from initial braking speed (IBS) of 80 to 380 km/hr. Coefficient of friction reduced from 0.395 to 0.358 with increase in IBS from 80 to 200 km/hr then increased to 0.398 when IBS reached 320 km/h; and fell again to 0.379 at 380 km/h. Similarly, the pad also displayed three wear regimes as IBS increased, i.e., (1) mild wear (80–160 km/h), (2) moderate wear (200–250 km/h), and (3) severe wear (300–380 km/ h). The formation or completion of friction film regularly contributes to a lower COF and wear rate, while the destruction of friction film results in a higher COF and wear rate. Besides, the ‘‘lubricants’’ induced by high braking temperature are also responsible for the change in the COF. As IBS increased, the key wear mechanisms changed from abrasion, plowing, and oxidation to delamination at 250 km/h.

Table 37: Composition of P/M pad as shown

Elements	Cu	Fe	Cr	Si	Al	Mo	S	C	O	Na	Ca	Mg
Mass (wt.%)	44.7	33.2	5.6	1.5	0.56	1.36	1.02	11.3	0.5	0.03	0.05	0.02





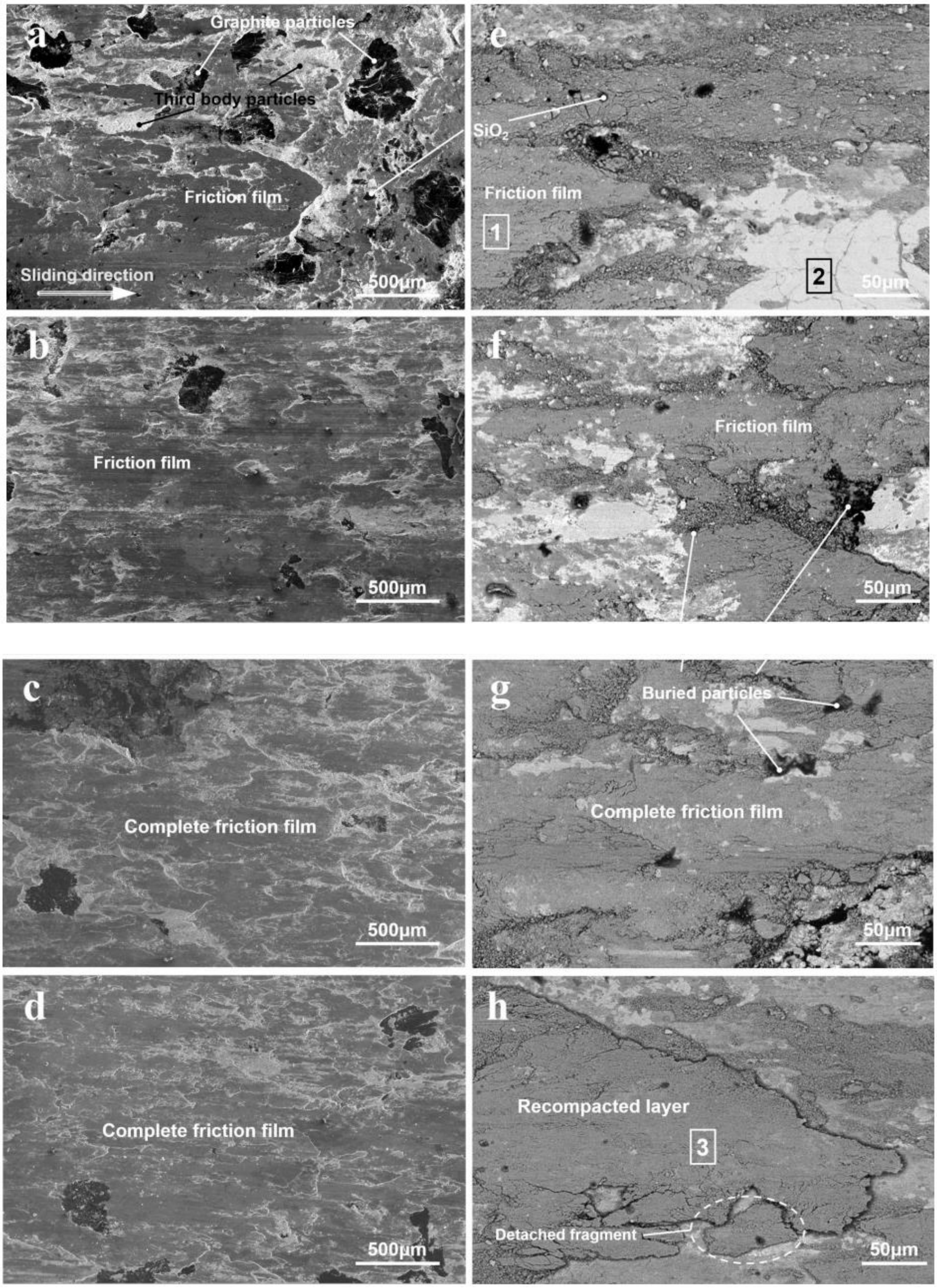


Figure 30. Worn surface SEM images at low speed.

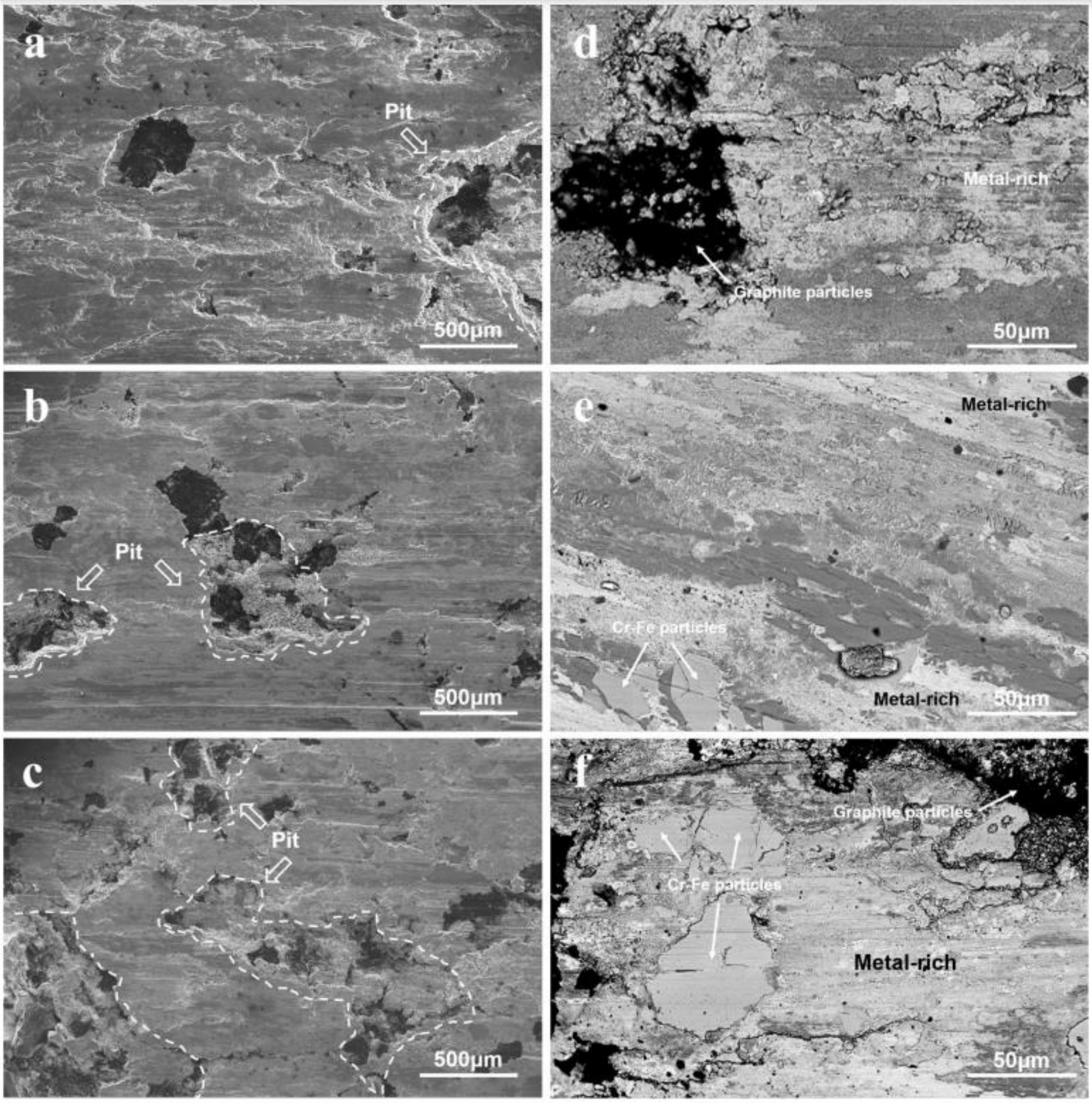


Figure 31. Worn surface SEM images at the medium-speed stage.

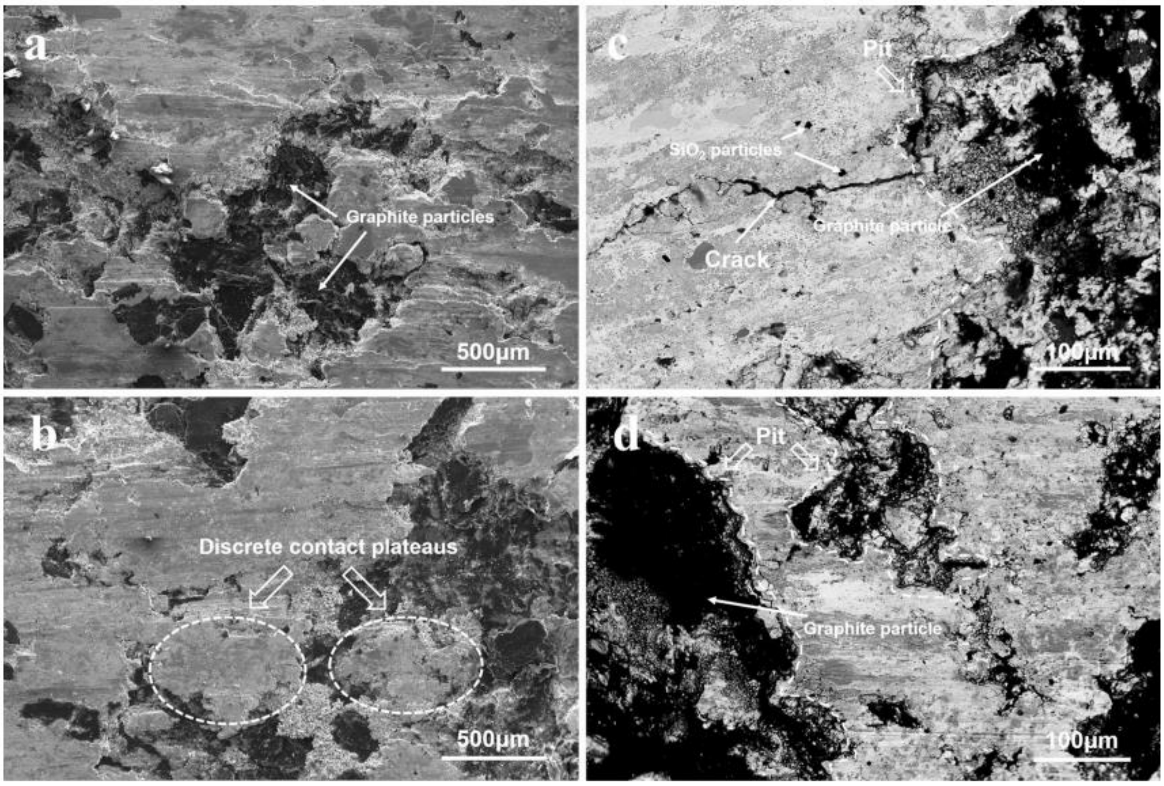


Figure 32. Worn surface SEM images at the high-speed stage.

Table 38: Summary of all the friction and wear behaviours and characteristics of friction film

IBS (km/h)	Friction behaviors	Characteristics of friction film	Wear behaviors	Wear mechanisms
80	Low-speed stage	A few patchy friction film	Mild wear	Abrasion, plowing and oxidation
	COF decreased from 0.395 to 0.358	Many exposed graphite, powdery and abrasive third body	$W_r \approx 10^{-5}$ mm³/J	
120		Continuous friction film		
		Buried graphite and hard particles		
160		Complete friction film		
		Buried graphite and hard particles		
200		Complete friction film	Moderate wear	
		A pieces of recompacted friction film	10^{-5} mm³/J $< W_r < 10^{-4}$ mm³/J	
250	Medium-speed stage	Slightly ruptured friction film		
	COF increased from 0.369 to 0.398	Some pits and exposed metallic surface		
300		Ruptured friction film	Severe wear	Delamination
		Some pits, exposed Cr–Fe particles and metallic surface	$W_r > 10^{-4}$ mm³/J	
320		Severely ruptured friction film		
		Many pits, crushed Cr–Fe particles, extensive metallic surface		
350	High-speed stage	Ruined and discrete friction film		
	COF decreased from 0.395 to 0.379	Many pits, exposed graphite and SiO_2 particles, cracks		
380		Ruined and discrete friction film		
		Many pits, exposed graphite and SiO_2 particles, cracks, as well as numerous molten holes		

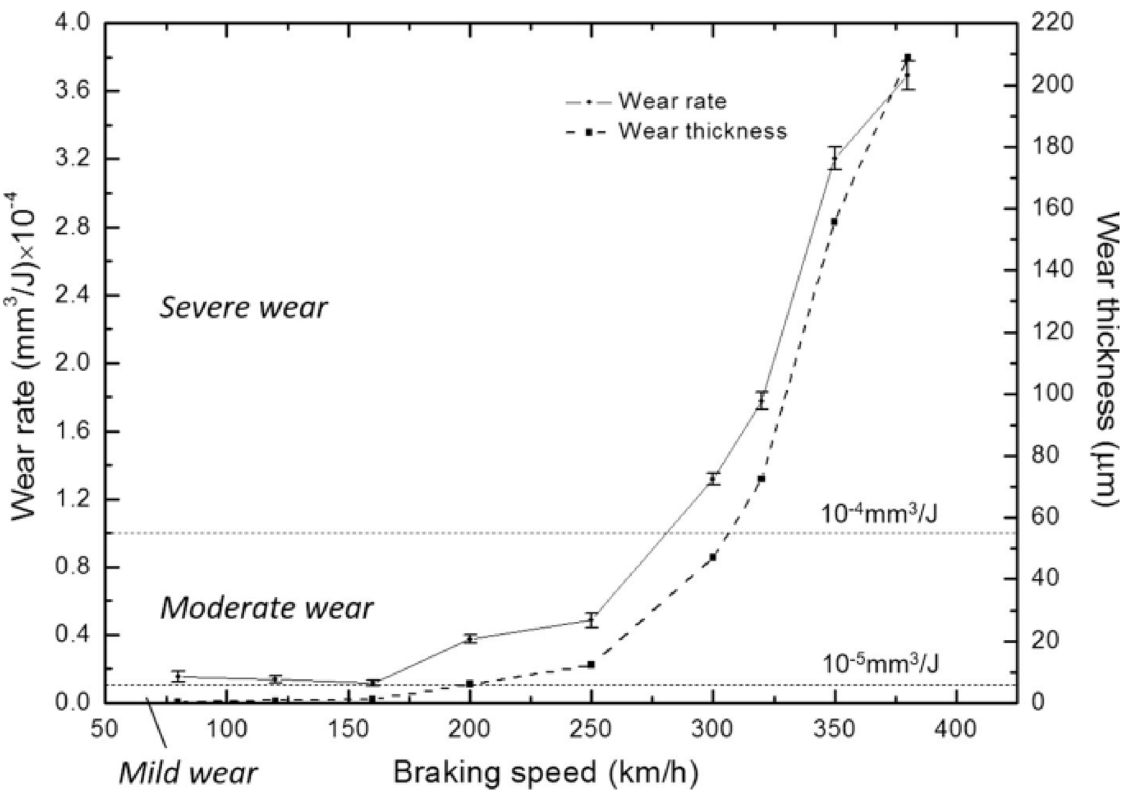


Figure 33. Plot of braking speed vs wear rate.

T. Miyauchi et al. [83]

This work focusses on importance of lubrication in sintered friction reducing pad wear in conclusive that the lubricant area fraction in sintered friction materials was the best values about 40 % to decrease wear of pad and disc. It was found that increasing the lubricant area fraction up to 40%, was effective in reducing pad wear. Above 40 % lubricant, wear rate either remained constant or increased slightly to decrease pad wear. The harder ST forged steel discs exhibited less wear than the softer FC and NCM cast irons.

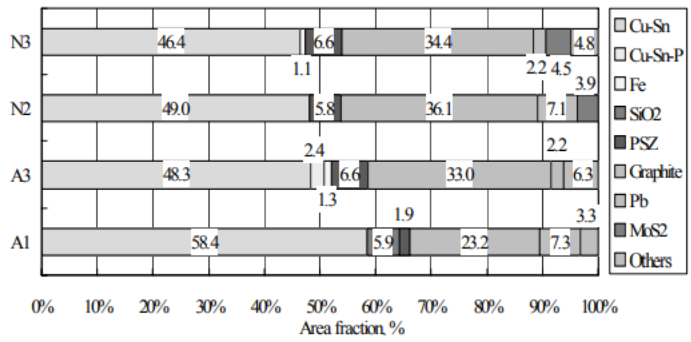


Figure 34. Average area fraction of phases

4. Conclusions

Following conclusions were drawn after reviewing considerable literature related to high speed railways, automobiles, wind turbine, elevators, aeroplane brake applications using various formulations:

1. Use of fly ash based **sintered materials** used in wind turbine brake pads have considerable effect in improving wear resistance but no study has been done testing the formulation of fly ash, red mud for high-speed railway sintered composite brake pads which can increase wear resistance and reduce carbon emissions simultaneously.

2. Friction forces produced by deformed primary plateaus, and secondary plateaus type II, are lower compared to those generated by non-deformed primary plateaus, and secondary plateaus type I, which were mainly formed on the surface of LM material. It was concluded that the deformed primary plateaus correspond to copper and brass fibers, while the non-deformable type are made from steel wool fibers but no study has been done on the use of novel fibres which could increase contact plateaus.

3. Cu-based alloys display a fade phenomenon at high temperature but from literature reviewed it has been found that few study has been done on synergetic use of iron powder with copper powder in order to reduce cracks and hot spots. Important role of lubricants in reducing sintered brake pad and disk wear.

4. Different friction block shapes can affect noise, vibration and harshness but from literature reviewed it has been found that little study has been done for reducing noise, vibration and harshness using new friction blocks shapes.

5. Brake disc wear study is missing which plays a vital role when the brake pad comes in contact with brake disc.

6. Effective solutions like adding a suitable elastic damping element to the back of the friction block should be considered to reduce the contact inclination angle of the friction block and spread the interface contact stress to avoid regions of concentrated contact stress.

8. Spallation and detachment are common problems associated with brake pads in service but no study has been done so far.

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