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Study of friction, wear and plastic deformation of automotive brake disc subjected to thermo-mechanical fatigue

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ABSTRACT

The function of the automotive braking system is to reduce the vehicle's speed or stop within a stipulated time. An efficient braking system dissipates all heat generated during braking into the environment before subsequent braking is applied. The heating and cooling cycles, in combination with mechanical loads during braking operation, cause thermal stresses on the surface of the brake disc. The resulting thermomechanical fatigue (TMF) on the brake disc is a life-limiting factor and causes failure. Understanding their impact, given experimental investigation using a full-scale inertia brake dynamometer is the paramount aspect. The reference disc, that is used for the experiment is a wheel-mounted brake disc. During the investigation, it is observed that (i) friction coefficient is sensitive to vehicle speed and braking pressure (ii) fade test records a maximum brake disc temperature of 403°C (iii) repeated thermal and mechanical cycles induced plastic deformation and cracks on the brake disc. The study provides insight into the parameters contributing to the damage at the friction surface of the brake disc that is subjected to Thermo Mechanical Fatigue (TMF).

Keywords: Automotive braking system; Disc Brake; Brake Dynamometer; Fatigue life; Brake fade-recovery. Brake wear.

1. INTRODUCTION

In automotive disc braking system, the ideal case of pad-disc contact would lead to a homogeneous distribution of contact pressure between the two friction surfaces. For various reasons, this ideal scenario can never be obtained as assumed in the design process. This will cause the material to experience high thermal stress and induce thermal shock. In addition, the heating and cooling cycles in combination with mechanical loads cause thermal stresses on the disc surface. The resulting thermomechanical fatigue (TMF) is a life-limiting factor [1]. Fatigue failures are dangerous as they are unpredictable, it gives no prior notification of the imminent failure but occurs suddenly. Fatigue failure is always a brittle fracture regardless of material property, whether brittle or ductile [2]. The objective of this experimental study is to investigate the Thermo Mechanical Fatigue response of the automotive brake disc.

Till now, a significant amount of literature exists on pad-disc interaction and tribology wear. PANIER *et al*. [3] discuss the thermomechanical modeling of the braking process. With these methods, the thermal input is introduced in a non-uniform manner to obtain quantitative results on the damage behavior. The non-uniform nature is established by modeling the disc-pad interaction. DESPLANQUES *et al*. [4] provide a discussion of a test parametric triplet factor linking the initial speed, the braking force, and the brake duration. The paper discusses the type of contact and consequently, the principal reason for the differing results is the difference in the loading conditions. RAJAN *et al*. [5] carried out tribological tests to understand the influence of binder on the brake pad. The paper talks about the characterization of the resin and composites using standard techniques. Tribological tests were carried out using an inertia brake dynamometer following JASO C427 industry standards. SARKAR and HIRANI [6] give insight into the frictional characteristics of the brake pads under thermo-mechanical conditions. He had attempted to characterize the friction behavior of Magnetorheological fluid brake. KIM [7] did comparative studies of high-speed train wheel tread brakes with composites brake block conditions in dry and wet conditions. The paper discusses about the occurrence of macroscopic hot spots that are linked to a certain level of dissipated energy in a sufficiently short time.

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The author understands the research done to date in this field and aims at bridging the gap between some aspects of research that have never been put together in the context of friction, wear, and plastic deformation of the brake disc under Thermo Mechanical Fatigue. A brake dynamometer permits lab testing for a vehicle's brake in actual size faster and more economical way to verify material friction characteristics [8]. Given the scope of the study on a full-scale test rig, the following conclusions have been drawn for the planning of the test rig program:

i. To investigate the wear rates of automotive brake discs under varying conditions of temperature, pressure, speed, and deceleration JASO C406 [9] Dynamometer test procedure is used.
ii. In a test sequence consisting of identical brake events and an increasing number of brake applications Thermo Mechanical Fatigue condition can be obtained. SAE J2707 [10], Wear Test Procedure on Inertia Dynamometer for Brake Friction Materials is used.

After dynamometer testing, the brake disc and its cross sections are subjected to various investigations to understand the impact of Thermo Mechanical Fatigue. A summary of the applied methods is given below:

i. A horizontal-arm coordinate measurement machine (CMM) manufactured by ZEISS Metrology Systems is used to measure the wear of the brake disc.
ii. Microstructural changes and fatigue cracking are investigated through the metallographic method using ZEISS EVO Scanning Electron Microscope.
iii. Brinell hardness testing of the brake disc before and after the wear test.

2. EXPERIMENT USING AN INERTIA BRAKE DYNAMOMETER

Dynamometer consists of a rotating disc, where the mass and moment of inertia are equivalent to those of the target vehicle. Dynamometer allows the brake disc rotates at the initial speed and braking force is applied to create frictional force between two contacted surfaces to decelerate. Throughout the wear characteristics test procedures, the inertia brake dynamometer imitates the real braking process of the automobile vehicle.

Figure 1 shows the interior of the dynamometer test bench used for this study. The test bench was manufactured by Mechsoft Technologies that meets dry and wet test requirements using braked mass. The dynamometer test bench consists of drive train parts with a motor, interchangeable flywheels, brake disc mounting fixtures, load bearing arm, load cells, etc. Application software enables the user to configure operating parameters (speed, operating temperature, braking pressure, etc.,) and control test sequences as per input schedules [11–13]. Brake cylinders will create braking force and the system acquires & records data like speed, torque, temperature, stopping distance, etc., for analysis. Specification of the Inertia Brake Dynamometer is given in Table 1.

A passenger car brake disc was chosen for the study. The test is classified as nominal maximum speed, which exceeds 90 km/h up to 110 km/h, following the provisions of JIS D0210 [14]. We ensured that the condition of each part of the brake devices used in testing complies with Item 4.3 of JIS D0210. To simulate the barking performance per the actual conditions, the governing parameter's inertia must be determined by the calculation equation specified in SAE J2789 [15].

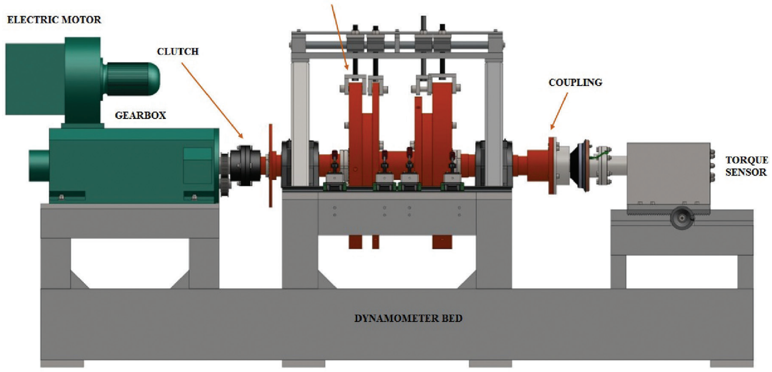

Figure 1: Schematic of inertia brake dynamometer.

Table 1: Technical specification of inertia brake dynamometer.

MOTOR	TORQUE (*max*)	SHAFT SPEED	INERTIA (*max*)	BRAKE TORQUE (*max*)	HYDRAULIC PRESSURE (*max*)	ENERGY DISSIPATED (*max*)
175 (*KW*)	9860 (*Nm*)	1500 (*rpm*)	15396 (*N-m²*)	9860 (*Nm*)	120 (*Bar*)	20 (*MJ*)

Required inertia is calculated using Equation 1 and Equation 2 and the inertia wheels are engaged to the main driving shaft. Considering 77% of gross vehicle weight (GVW) and a rolling radius of 225 mm the inertia value is determined from Equation 1 as 15 kg/m^2.

$$I = m \cdot r_{dyn}^2 \quad kg.m^2 \tag{1}$$

I Rotary inertia ($kg.m^2$)

r_{dyn} The dynamic rolling radius of the tire (m)

m Test mass (kg)

$$m = \frac{0.77 \cdot m_{veh}}{2 \cdot n_{front}} kg \tag{2}$$

m_{veh} the maximum permitted mass of the vehicle (kg)

n_{front} number of front axles

Table 2 shows the brake disc and test parameters of a passenger car. The new brake assembly is mounted on the dynamometer, replicating the actual installation on the vehicle on which it is usually fitted, refer to Figure 2. The brake disc assembly was inspected to confirm no abnormalities and ensured that no foreign matter, including grease, paint, etc., was present on the surface of the friction material. Thermocouples were installed at the specified location on the pad. Cooling wind at room temperature is allowed to blow continuously on the brake disc surface at 11 *m/s*. The major factors which determine the brake power of the system are (i) mass and speed of the vehicle (ii) stopping distance and deceleration rate (iii) pressure applied on brake pads (iv) coefficient of friction between disc and pads (v) initial brake temperature (vi) environmental conditions (ambient temperature and wind) and tire-ground contact conditions. For vehicle-level testing, brake performance

Table 2: Brake disc and test parameters of passenger car.

GROSS VEHICLE WEIGHT	VEHICLE CATEGORY	BRAKE TYPE	DISC MATERIAL	ROTOR DIAMETER	ROTOR THICKNESS	TEST INERTIA	ROLLING RADIUS
1185 (*kg*)	P2	Disc Brake	EN-GJL-250	280 (mm)	22 (mm)	15 ($kg.m^2$)	225 (mm)

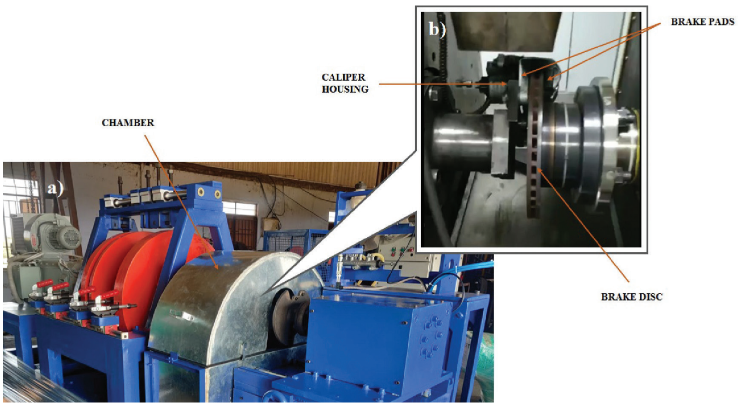

Figure 2: (a) Full-scale inertia brake dynamometer test setup (b) Brake disc assembly.

is measured by stopping distance or deceleration as a function of pedal force. But for inertia brake dynamometer testing, stopping distance is replaced by brake output torque, and brake pedal force is replaced with brake pressure. The motor is engaged and accelerated to the required speed. When it reaches the needed speed, the motor is disengaged to allow the drive-train assembly to run free due to the inertia generated by the flywheel. A brake is applied to make the brake pads engaged with the brake disc. This action causes the drive-train to reduce the speed or to stop against the inertia generated by the flywheel. The kinetic energy generated by the flywheel is matched to the energy generated by the vehicle in an actual braking scenario. Brake pressure, Torque, Disc temperature, etc. are captured.

2.1. Experimental study on the effectiveness of friction material

True catastrophic failure of the braking system is most commonly associated with brake fade. This test aims to assess the behavior and effectiveness of friction material with respect to temperature, braking pressure, and speed of the vehicle. The friction behavior assessment test was carried out following JASO C406. Inertia brake dynamometer test sequences are shown in Table 3.

Each test schedule is explained below.

Green μ; Brake pads are made with different materials and bound together with resins. These resins are one of the vital parameters for reducing friction. Gaseous bearing fade is said to occur when the resin gasses escape from the brake pad surface while it gets overheated. New brake pads may release gases as they reach a high temperature. The released gases form a layer and create a loss of friction called the green fade. Green μ is to prepare the pads and discs for maximizing their performance and longevity during testing. 10 cycles of the pre-burnish check were performed with an initial braking speed of 50 km/h and braking deceleration 3.0 m/s^2 while maintaining the initial brake temperature at 80°C. It's the first contact between the brake disc and the pad.

Burnishing; incomplete contact between the brake pad and the brake disc will contribute to friction fade. Due to insufficient contact, the heat distribution will not be even across the friction surface. This condition causes the brakes to heat quickly to the point of friction fade. It must be noted that a disc's surface showing signs of blueing is subjected to incomplete friction surface contact. Irregularities are also the causes of green fade, which distributes uneven braking pressure until the friction surface is burnished. To avoid green fade and improper contact, bedding is being done. It is a process of bringing the pads to high temperature and transferring a layer of brake pad material onto the brake rotor. This provides improved braking power and smoother brake operation. 200 cycles of burnishing test with initial braking were done with a speed of 65 km/h, and braking deceleration 3.5 m/s^2 while maintaining the initial brake temperature as 120°C. Snub braking is applied to measure the stopping efficiency of the vehicle under variable load and speed conditions.

Fade & recovery; as discussed early in this article, converting the vehicle's kinetic energy into heat energy using friction is the function of the braking system. The ability to convert the kinetic energy will get reduced once the friction reduces below the acceptable level. The repeated braking application under high loads and speeds causes excessive heat in the braking system. This, in turn, results in a temporary and sudden reduction in braking power called friction fade. When Friction fades, pedaling becomes more challenging for the driver, who can also feel the difference in braking response. This test sequence quantifies the fade and recovery of the brake disc.

Table 3: Friction behavior assessment test sequence per JASO C406.

SCHEDULE	INITIAL BRAKING SPEED (kg/h)	BRAKING DECELERATION (m/s^2)	INITIAL BRAKE TEMPERATURE (°C)	REPETITIONS
Pre burnish Check	50	3.0	80	10
First effectiveness test	50 & 100	3.5	80	10
Burnish	65	3.5	120	200
Low-temperature effectiveness	50	3.5	50	10
Normal temperature effectiveness	50, 80 & 100	3.5	80	10
First reburnish test	65	3.5	120	35
First fade	65	3.0	60	10
Second fade	65	5.0	60	15

Table 4: SAE J2707 wear test procedure for brake friction materials.

SECTION	INITIAL SPEED (kg/h)	INITIAL DISC TEMPERATURE (°C)	BRAKING DECELERATION (m/s²)	REPETITIONS
Burnish	80	100	3.0	200
Wear Test 100°C	50	100	3.0	1000
Wear Test 200°C	50	200	3.0	1000
Wear Test 300°C	50	300	3.0	500
Wear Test 400°C	50	400	3.0	200
Wear Test 500°C	50	500	3.0	200

Effectiveness (Pressure-speed sensitivity) quantifies the influences of vehicle speed and braking pressure on braking performance.

Speed sensitivity examines braking consistency at different vehicle speeds and braking pressure.

Test values of torque, pressure, temperature, and initial braking speed are recorded for each test. Force and braking torque are measured constantly. Conditions of wear pads and discs before and after the tests are recorded. The results of the test are discussed in (3.0).

2.2. Experimenting with thermo mechanical behaviour of the disc

The test aims for the brake disc to undergo thermomechanical fatigue and investigate the wear and plastic deformation of the brake disc. SAE J2707 test procedure is used for identical and repeated braking events and the test sequences are shown in Table 4. In friction behavior assessment (1.2), during the first fade testing, it was observed that the maximum temperature experienced by the brake disc was 403°C. Hence the test sequence was limited up to 500°C. Braking torque was provided by controlling and modulating the brake pressure. Thermocouples were installed on the inner face of the brake disc at the effective radius. Initial brake disc, pad thickness, and other dimensions are measured and recorded as per SAE J2986 [16], ISO 26867 [17] SAE J2986 [18]. Ensured no grease or any foreign matter adhered to the brake pads. The brake cooling air temperature was maintained at 30°C and humidity at 45% RH. The results of the test are discussed in 3.0.

3. RESULTS AND DISCUSSIONS

3.1. Assessing fade resistance

Fade resistance is determined by the temperature at which the brake fade occurs. It is also determined by a minimal change in the coefficient of friction that friction material undergoes after brake fade occurs. Generally, the fade point for the passenger car would be between 300°C and 350°C. And the fade resistance is between 60% and 80%. The fade rate observed is 69.57% and 74.47% (refer to Tables 5 and 6) after the first and second fade test sequence, respectively. The acceptable recovery rate as per industry standard is 80% and above while recovery rates after the first and second fade are 88.8% and 91.1%, respectively; refer to Table 5 and Table 6.

Table 5: First fade and recovery rate.

FIRST FADE & RECOVERY TEST		
Fade	Initial	0.49 μ
	Maximum	0.49 μ
	Minimum	0.32 μ
	Max Temp	403°C
	Fade Rate	69.57%
High-Temperature Effectiveness		0.32 μ
Recovery	Baseline	0.47 μ
	Recovery	0.42 μ
	Recovery Rate	88.88%

Table 6: Second fade and recovery rate.

SECOND FADE & RECOVERY TEST		
Fade	Initial	0.47 μ
	Maximum	0.47 μ
	Minimum	0.35 μ
	Max Temp	456°C
	Fade Rate	74.47%
High-Temperature Effectiveness		0.32 μ
Recovery	Baseline	0.45 μ
	Recovery	0.41 μ
	Recovery Rate	91.10%

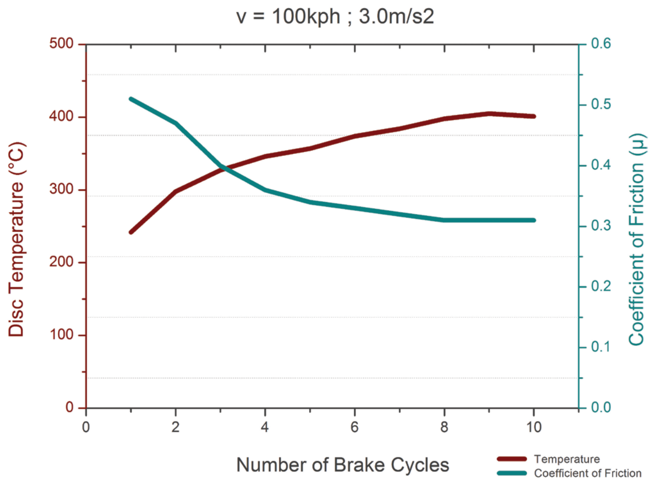

Figure 3: Influence of temperature on friction during first fade sequence.

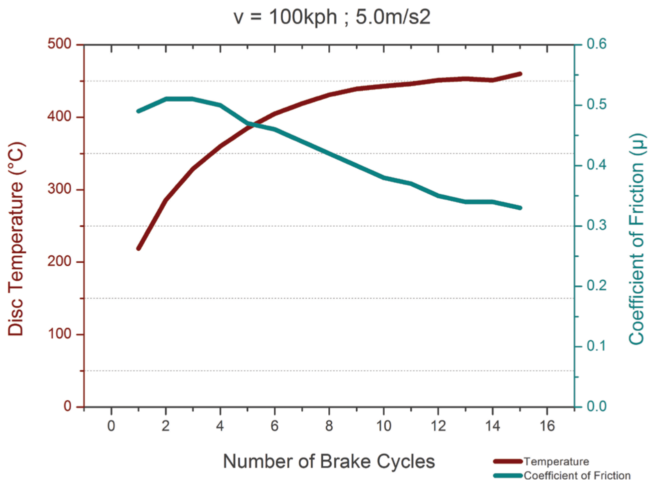

Figure 4: Influence of temperature on friction during second fade sequence.

3.2. Assessing the influence of brake disc temperature

The fade test highlights the effect of temperature on the brake disc and pad. It could be noticed from Figure 3 and Figure 4 that the friction coefficient decreases when there is an increase in temperature. It is also observed that the maximum temperature experienced by the brake disc is 403°C. The coefficient of Friction is sensitive to temperature [6]. Friction increases to a certain point and begins to drop, following a curvilinear pattern, refer to Figure 5. The brake disc becomes red hot during the wear test (refer to Figure 6). Due to the high temperature, the brake pads will transfer a layer of friction material onto the surface of the brake disc, this can be investigated

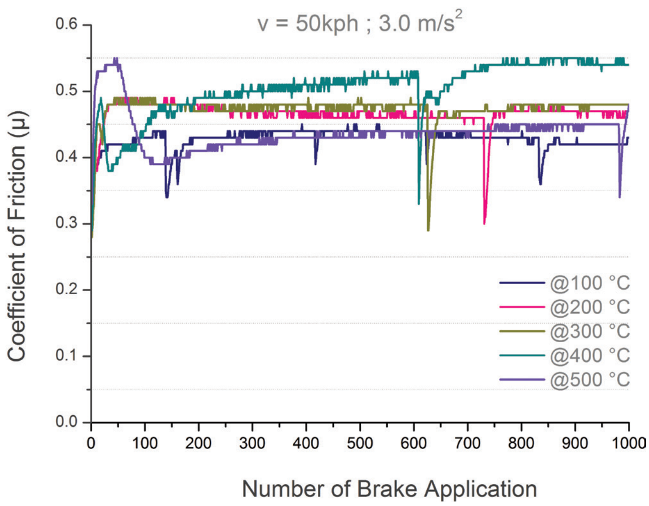

Figure 5: Influence of temperature on friction during the wear test.

Figure 6: Red hot condition of brake disc during wear test.

using Scanning Electron Microscope. The pads rubbed on the brake disc surface would have created irregular heat build-up across the disc [19]. If the temperature of the brake disc crosses 650°C, the brake disc material, cast iron, changes its structure and transforms into a hard material called cementite. The cementite structure will create high spots that can lead to brake judder and premature disc wear [20, 21]. The brake judder is the most critical NVH problem, and it is a forced vibration proportional to the vehicle's speed. A brake judder can induce vibration in steering wheels, brake pedals, suspensions, and even the entire car body. This will create a concern for passenger comfort.

3.3. Assessment of coefficient of friction and wear

Friction surface temperature is a vital factor that affects brake friction. Smaller the friction coefficient means smaller the brake force required for the two surfaces to slip. Similarly stronger forces is required while in case of higher friction coefficient. Coefficient of friction is measured using the parameters (Speed, Forces, braking moments etc.,) that are specified in Table 1 and 2. Speed sensors and load cells are mounted in the dynamometer to measure the net moment acting on the wheel. Using the below equations friction force and friction coefficient are calculated for each braking cycle.

$$M_{net} = M_{br} + M_{fr} + M_i \tag{3}$$

$$\mu = \frac{M_{fr}}{r_d \times F_n} \tag{4}$$

M_{net} Moment measured by load cell

M_{br} Braking moment

M_{fr} Friction moment
M_i Inertia moment
r_d Radius of tyre
F_n Normal braking force

It is essential to have a stable friction coefficient at various temperatures. Brake pad friction will gradually decline in the linear pattern Figure 4 when heat builds on the surface. Alternatively, brake pad friction could follow a curvilinear pattern where the friction coefficient gradually increases to a particular point and quickly drops. In practice, linear Friction- temperature relationship pattern is desired. In this pattern, the fade is gradual and hence predictable. From Figure 7, we could absorb μ increase gradually and becomes stable after a few brake cycles. Ideally, μ should be anything between 0.35 and 0.5 and have a minimal slope.

The coefficient of Friction of the first and second fade sequences is within an acceptable level, and it has to be noted that a higher coefficient of Friction requires less braking pressure to create a high braking force. Figure 8 shows a gradual reduction in μ but stabilizes after a few cycles. Friction coefficients measured after all the test sequences are listed in Tables 7 and 8. Also, changes in disc thickness before and after the wear test are measured using a horizontal-arm coordinate measurement machine, refer to Figure 9. The accuracy is increased by increasing the number of measuring points. The disc is divided into eight equal segments. Wear is derived by 40 measuring points @ 5 measurements on each segment, and measured values are shown in Table 9.

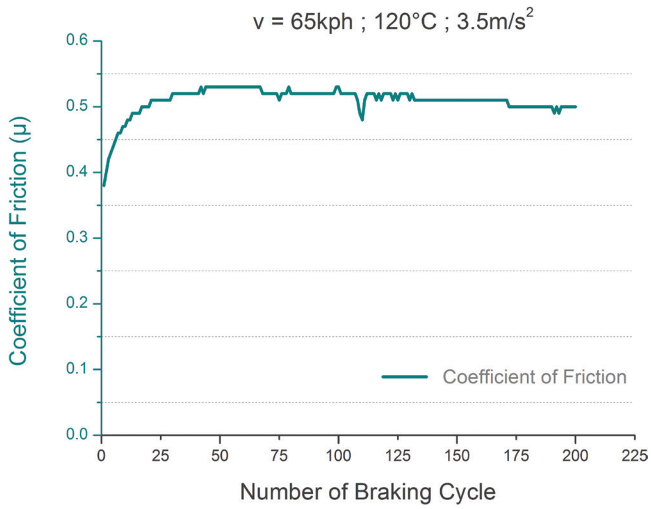

Figure 7: Influence of the number of braking cycles on friction.

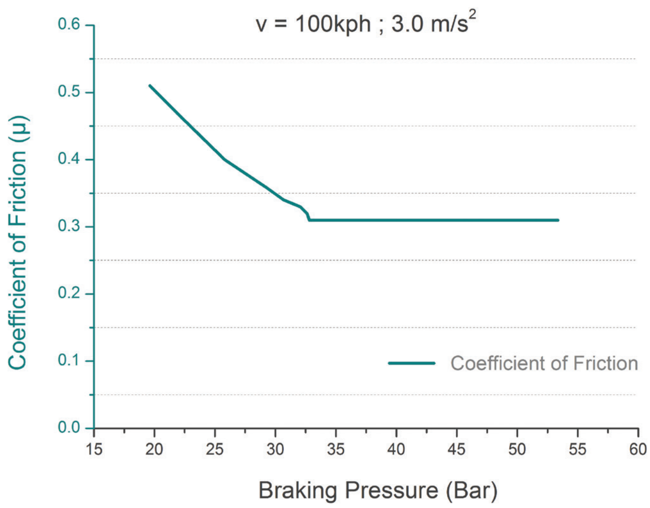

Figure 8: Influence of braking pressure on friction.

Table 7: Influence of speed and temperature on friction.

EFFECTIVENESS TEST		
1st Effectiveness	50 km/h	0.39 μ
	100 km/h	0.43 μ
Low Temperature (50°C)	50 km/h	0.41 μ
2nd Effectiveness	50 km/h	0.42 μ
	100 km/h	0.46 μ
	130 km/h	0.40 μ
3rd Effectiveness	50 km/h	0.51 μ
	100 km/h	0.51 μ
	130 km/h	0.45 μ
	150 km/h	0.41 μ
Speed Fade @ 0.6g		98.52
Stability at 80 km/h; 0.6g (%)		110.87

Table 8: Friction coefficient after burnishing.

BURNISHING	
Burnish	0.51 μ
First reburnish	0.47 μ
Second reburnish	0.47 μ
Third reburnish	0.50 μ
Fourth reburnish	0.46 μ

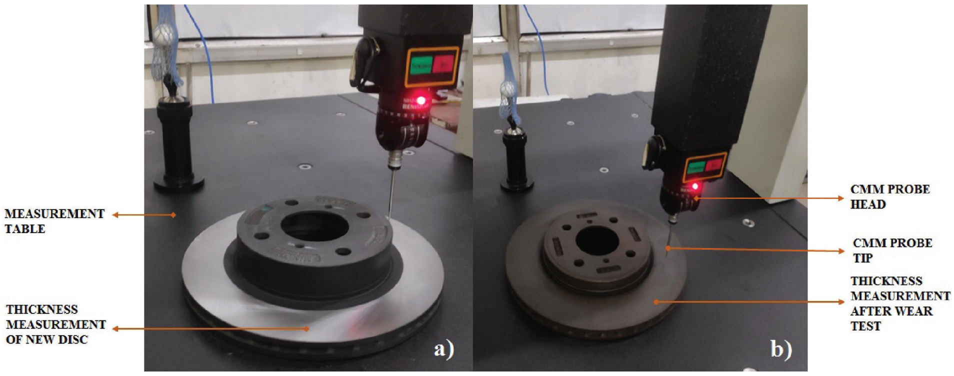

Figure 9: (a) Thickness measurement of new disc in CMM (b) Thickness measurement after wear test.

Table 9: Brake disc wear.

BRAKE DISC WEAR			
	INNER PAD	OUTER PAD	DISC
Wear	0.22 (mm)	0.25 (mm)	0.074 (mm)

3.4. Assessing microstructural damages

Due to the high-temperature levels at the friction surface during high energy braking, significant changes in the microstructure of the material can occur. The resulting microstructure is highly dependent on thermal levels and heating/cooling rates. For this reason, metallographic investigations yield a significant amount of information on the thermal loading conditions. The segment was separated by a precision cutting machine according to the sampling plan. The scanning electron microscope (SEM) uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. The signals that derive from electron-sample interactions reveal information about the sample including external morphology (texture), chemical composition, and crystalline structure and orientation of materials making up the sample. Figure 10 shows a global view of the prepared metallographic specimens and the investigated positions. Based on these specimens the base microstructure, the individual transformed zones, and their penetration depths are determined, refer to Figures 11 and 12. Specimens were investigated under a magnification range between 10× and 10,000× with a spatial resolution of 2 *nm*.

Figure 11 shows the traces of the friction material on the surface of the brake disc. This might have occurred due to the transfer of the friction material from brake pads at high surface temperatures. The wear rate is proportional to the temperature, and it will be more severe at higher temperatures.

The heating and cooling cycles, in combination with mechanical loads during braking operation (3.2), cause thermal stresses on the surface of the brake disc. The resulting thermal and mechanical fatigue (TMF) could have induced plastic deformation. The heat generated due to friction might have caused changes in the

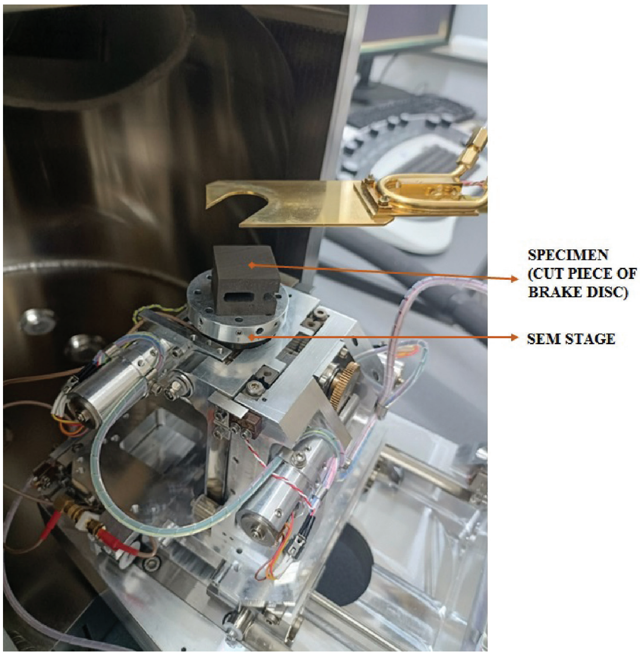

Figure 10: The specimen under metallography testing.

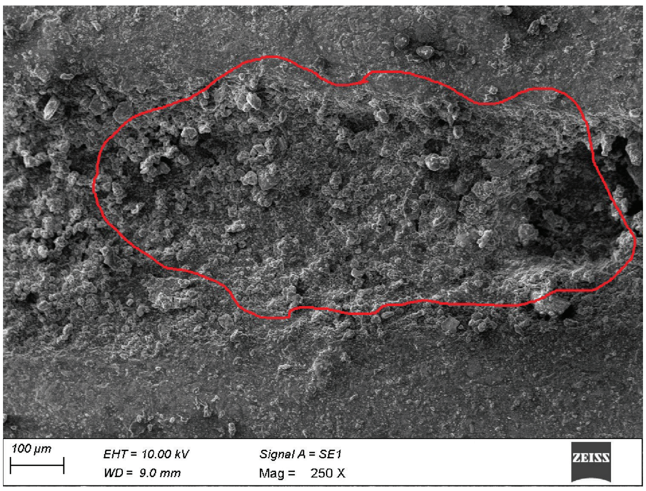

Figure 11: Traces of friction material on the brake disc surface.

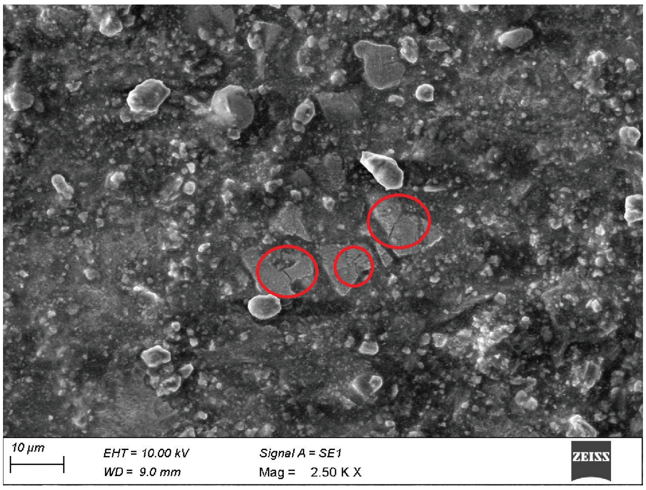

Figure 12: Cracks on the surface of the brake disc.

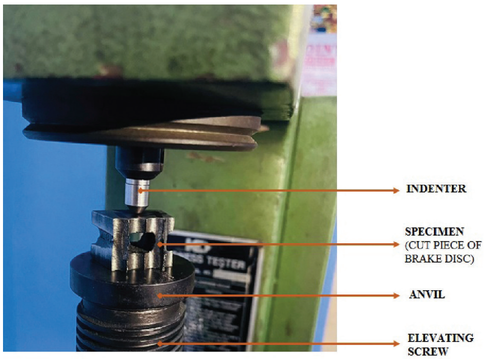

Figure 13: Hardness testing of the specimen.

Table 10: Brake disc surface hardness.

Load applied	187.5 *kgf*
Indenter	2.5 mm ball
Surface hardness (Before wear test)	187 *BHN*
Surface hardness (After wear test)	229 *BHN*

surface microstructure and structural phase transformation of the brake disc material. Furthermore, the local changes in the microstructure have a great impact and entail the formation of micro cracks that is observed on the brake disc; refer to Figure 12.

3.5. Assessing surface hardness

To understand the surface hardness between the virgin brake disc and the brake disc that underwent the wear test were subjected to a hardness test, refer Figure 13. The objective is to find whether the surface becomes hard to induce cracks during the fatigue cycle. The Brinell hardness of both samples was tested as per ASTM E10. It is found that there is an increase in the surface hardness of the brake disc that is subjected to the wear cycle. But, the surface hardness of 229 *BHN* is not alarming, refer Table 10.

4. CONCLUSION

From this study, it is evident that temperature and cyclic mechanical braking force strongly interact to form a complex damage process. For any reliable design, it is often sufficient to have fast qualitative simulation results at hand. They are supposed to show whether the thermo-mechanical life will increase or decrease, severely or at a moderate level. The authors aim to develop a numerical approach for life prediction of brake discs that are subjected to Thermo Mechanical Fatigue. The material behavior and the global loading conditions must be captured for this purpose. The following behavior and effectiveness of friction material concerning temperature, braking pressure, and speed of the vehicle observed during this study will be considered during the development of the numerical approach.

i. Brake wear: The impact of disc wear starts to play a role after a high number of brake applications but it is difficult to pinpoint a clear trend. Especially the measurements in the worn regions yield ambiguous results. This is because the wear is not homogeneous along the radius, as outlined in [19].
ii. Friction coefficient Vs speed: The coefficient of Friction is sensitive to vehicle speed. This finding is in line with [4] which discusses the relation between initial speed, braking force, and brake duration.
iii. Friction coefficient Vs braking pressure: Additionally in this study, it is found that there is clear evidence of the influence of braking pressure on the coefficient of Friction. Friction increases to a certain point and begins to drop, following a curvilinear pattern.
iv. Friction coefficient vs temperature: Important observation of the study is the stability of the coefficient of friction at various temperatures. Usually, the friction coefficient is lower at low surface temperatures and also at extremely high temperatures [6]. But, the investigation shows that a stable friction coefficient at different disc temperatures can be obtained with the quality brake compound.
v. Maximum disc temperature: The fade test records a maximum disc temperature of 403°C (First Fade). Though increased disc temperature is not the influencing factor for friction coefficient but brake pads transferred a layer of the friction material on the brake disc surface.
vi. Micro cracks: The heat generated caused changes in the surface microstructure and structural phase transformation of the brake disc material. Furthermore, the local changes in the microstructure have a great impact and caused micro-cracks on the brake disc. The further study shall be done to characterize residual stresses formed in the brake disc due to cyclic plasticity and metallurgical transformations.

The investigation provides insight into the parameters contributing to damage at the friction surface of the brake disc that undergoes thermomechanical fatigue. The obtained knowledge is the basis for the development of a numerical approach.

5. ACKNOWLEDGEMENTS

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