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THE EFFECT OF TEMPERATURE ON THE GENERATION OF THERMOINSTABILITY DURING BRAKING OF FRICTION LINING MATERIALS

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Abstract. In braking process, kinetic energy is converted to heat energy and the friction lining materials and brake pads absorb this heat energy before being released to the atmosphere. This accumulated heat energy may cause the automotive friction lining materials to experience high temperatures and this may affect the braking performance. In this study, the braking process was simulated by pressing a pair of brake pads against a rotating pearlitic gray cast iron brake disc at a constant rotating speed of 750 rpm. The test samples were subjected to continuous and intermittent brakings. In continuous braking, each sample was subjected to five different braking times of 3, 6, 9, 12, and 15 minutes and applied loads of 100, 200, 400, 600 and 800 N, whereas, in intermittent braking each sample was subjected to an applied load of 600 N and four different braking times of 400, 800, 1200 and 1600 seconds. Each sample was then observed under the Scanning Electron Microscope (SEM). Microstructural examinations showed that thermoinstability starts with the formation of thermogrannules at the contact area as a result of high temperature generated during braking. Accumulated heat on the contact area introduced thermal stresses which will then superimpose onto the mechanical stress, resulting in the generation of thermomicrocracks. Based on the microstructural results, it was postulated that microcrack propagated, grew and finally joined together to form multiple microcracks as the braking time increased. Subsequently, upon reaching a critical length, the wear particles are disposed from the wear surface.

Keywords: Brake pads, thermoinstability, thermogranules, thermomicrocrack, wear

Abstrak. Tenaga kinetik yang terhasil semasa proses pembrekan ditukar kepada tenaga haba dan bahan pelapik brek dan pad brek menyerap tenaga haba sebelum dilepaskan ke atmosfera. Tenaga haba yang terkumpul boleh menyebabkan bahan pelapik geseran automotif mengalami suhu yang tinggi dan memberi kesan kepada prestasi pembrekan. Dalam kajian ini, proses pembrekan disimulasi dengan menekan sepasang pad brek ke atas piring brek besi tuang kelabu pearlitik yang berpusing pada kelajuan pusingan malar 750 pusing seminit. Sampel dikenakan pembrekan berterusan dan berkala. Setiap sampel semasa pembrekan berterusan dikenakan lima masa pembrekan iaitu 3, 6, 9, 12, dan 15 minit dan beban kenaan 100, 200, 400, 600 dan 800 N. Manakala, setiap sampel semasa pembrekan berkala pula dikenakan kepada beban kenaan 600 N dan empat masa pembrekan berlainan iaitu 400, 800, 1200 dan 1600 saat. Seterusnya setiap sampel diperhatikan dengan menggunakan Kemikroskopan Elektron Imbasan (KEI). Pemeriksaan mikrostruktur menunjukkan ketidakstabilan bermula dengan pembetukan bebutir haba pada kawasan sentuhan hasil daripada suhu yang tinggi terjana semasa pembrekan. Haba terkumpul pada kawasan sentuhan menghasilkan tegasan haba yang

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mana akan menindih ke atas tegasan mekanikal, menyebabkan penjanaan mikroretak haba. Berdasarkan kepada keputusan mikrostruktur, dicerapkan bahawa mikroretak merambat, membesar dan akhirnya bertaut antara satu sama lain membentuk mikroretak berbilang apabila masa pembrekan ditingkatkan. Seterusnya, zarah haus tersingkir dari permukaan haus setelah mencapai jarak kritikal.

Kata kunci: Pad brek, ketidakstabilan haba, bebutir haba, microretak haba, haus

1.0 INTRODUCTION

A brake system is used to slow down a moving vehicle which will finally stop at the required distance. It is also used to hold the vehicle stationary in parking position. When a driver presses the foot pedal, the driver's muscular force is applied to the brake pedal and the attached master cylinder push rod. This in turn, pushes the master cylinder push rod and subsequently moves the master cylinder piston and creates a hydraulic pressure in the system. The pressure generated in the system moves the wheel cylinder piston against the brake pad or shoe, and force the brake lining materials against the disc or drum. When this happens, the friction between the lining material and the drum or disc will result in slowing or stopping the car. In the process of decelerating a moving vehicle, kinetic energy (momentum) is converted into thermal energy (heat). This accumulated heat is absorbed by the brake pads and brake disc before being dissipated to the atmosphere. The accumulation of heat causes high surface temperatures in the lining materials and the brake disc. This, in turn causes the generation of thermoinstability in the brake system [1,2,3,4].

Friction materials are generally composed of a mixture of five main constituents, namely; fibre, resin, modifier, filler, and additives [5]. Resins act as a binder and hold the compositions together. Too much resins in the composition will result in thermal instability and cause friction coefficient to be reduced. On the other hand, if it is too low, wear rate will increase as a result of less binding properties and difficulty in getting a uniform dispersion. Surface temperature increases when the operating variables such as load, speed, and braking time are increased [6]. As the surface temperature increases, the polymer materials will degrade. The onset of degradation of the friction materials start at 230°C, and the degree of degradation increase with temperature within the range of 269 – 400°C [7]. The degradation of the polymer materials may cause brake to fade, in which the friction is reduced as the temperature increased [8,9]. This sudden drop of friction results in lower brake performance, in which longer braking distance is required before the moving vehicle can be stopped.

Surface temperature will increase as the braking time, speed, and applied load increases. Surface temperature is high at the contact area during sliding and this causes local area to expand [3]. The high temperature will also decrease the yield strength and leads to changes in the wear mechanism and real contact configuration [10]. In another study, Ting [11] proposed a thermal-mechanical theory, where the temperature rise at the asperity introduced thermal stresses which could superimpose onto the mechanical stresses. This process increases the total contact stress and facilitates the onset of plastic yielding. The asperity contact results in a high flash temperature. The contact area grows and finally hot patches are generated as sliding progresses. The size of the patches generally depends on the normal load and the properties of the contacting materials [2]. The temperature of hot patches can reach the melting points of the materials [2].

Earlier studies have shown that microcracks generated on the surface are due to thermoelastic instabilities and frictional stresses [12]. Barber hypothesised a condition whereby one region of the surface is heated to a temperature slightly higher than the surrounding areas [1]. This phenomenon causes higher thermal expansion, which will produce higher pressure and temperature in that region, resulting in more localised thermal expansion. The greater expansion of this hot region as compared with the surrounding areas leads to the generation of large compressive stress component. This phenomenon may result in tensile stresses upon cooling and such repeated thermoinstability may lead to microcracks initiation and propagation. Once microcracks have nucleated, they will grow and propagate with subsequent brakings, and finally join each other to form multiple microcracks [13].

In this study, the process of generation and propagation of thermomicrocracks in semi-metallic brake pads is discussed. The microstructural changes on the wear surfaces as well as in the bulk of the brake lining materials were observed using scanning electron microscopy (SEM).

2.0 MATERIALS AND METHODS

All samples were subjected to friction tests as previously described in an earlier published paper [6,14]. In short, two test samples were cut from the brake pad backing plate with dimensions of 20 ± 1 mm × 30 ± 1 mm × 15 ± 1 mm. These samples were glued to the backing plate and placed in the oven at 180°C for one hour to ensure that they were properly glued to the backing plate. This backing plate was then attached to brake callipers on both sides of the brake disc. The friction tests were carried out by pressing test samples against a rotating brake disc (Figure 1).

The test samples were subjected to continuous and intermittent brakings. Four samples of different models and makers were used in this study and marked as A, B, C, and D. Sample A, B, C, and D were used in intermittent braking and only sample D was used in the continuous braking test. Table 1 shows the organic and metal content of the samples as obtained using thermogravimetric analysis. Table 2 shows the metallic composition of the samples using Energy Dispersive Analysis of X-Ray (EDAX).

In continuous braking, each sample was subjected to five different braking times of 3, 6, 9, 12, and 15 minutes and applied loads of 100, 200, 400, 600, and 800 N. On the contrary, the samples tested in intermittent braking were subjected to four different total braking times of 400, 800, 1200, and 1600 seconds and an applied load of 600 N.

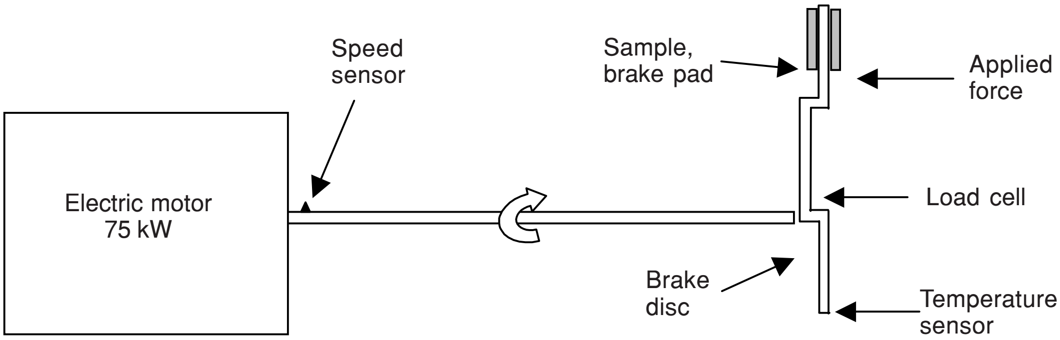

Figure 1 Friction test machine layout

Table 1 Organic and metallic contents

Elements	**Weight %**			
	Sample A	**Sample B**	**Sample C**	**Sample D**
Organic	32.32	50.13	16.12	14.22
Metallic	67.78	49.87	83.88	85.78

Table 2 Metallic composition of the sample

Element	**Weight %**			
	Sample A	**Sample B**	**Sample C**	**Sample D**
MgK	11.67	8.19	1.46	1.38
AlK	4.56	–	1.87	2.38
SiK	–	–	4.37	4.96
MoK	7.45	76.94	–	–
S K	–	–	3.97	5.88
K K	–	–	1.33	0.61
CaK	7.75	5.67	0.67	0.87
CuK	13.35	–	–	–
TiK	12.08	–	3.25	5.37
Ba	20.87	0.49	0.95	–
FeK	22.27	8.71	82.13	78.52
Total	100.00	100.00	100.00	100.00

In the intermittent braking, the brake was applied for 80 times. In between braking, the brake was in the OFF position for 5 seconds. The brake was set to four different braking times of 5, 10, 15, and 20 seconds. Details of the intermittent braking procedures can be referred to an earlier published paper [14]. The rotating velocity of the brake disc in both cases were kept constant at 750 rpm for both continuous and intermittent braking modes.

The morphological changes on the surface and subsurface were observed using Scanning Electron Microscopy model PHILIP SL 300. Samples for surface examination were cut from the backing plate, cleaned with compressed air and then coated with gold. Samples for subsurface examination were further cut parallel and perpendicular to the sliding surface using a fine cutter. The samples were mounted and polished to a surface finish of 1 μm. Prior to microstructural examination, the samples were coated with gold using a Polaron sputter coater.

3.0 RESULTS AND DISCUSSION

Automotive friction material is a non-homogeneous material, composes of resin, organic, and metallic material as well as reinforced fibre materials (Figure 2). The formation of thermal granules occurred in the early stage of thermal wear. Heat accumulated on the automotive lining materials during braking, resulting in high temperature on the

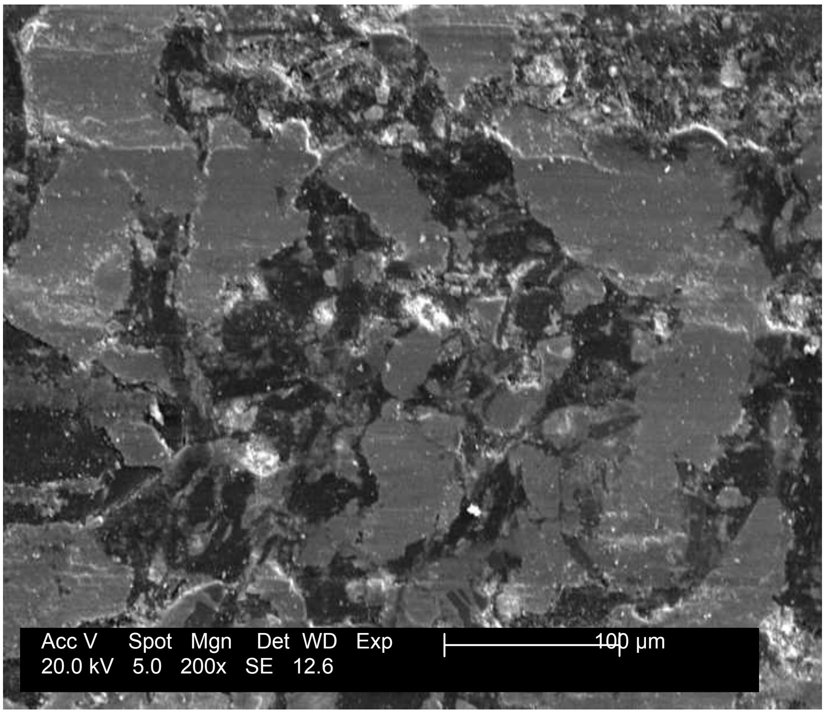

Figure 2 Micrograph of brake pad as polished using sand paper 1000 grid

contact areas. This in turn, caused thermoinstability on the contact areas, and subsequently, the formation of thermal granules. As the temperature increased, some of the metal elements in the lining material started to melt and formed metal droplets on the interface of the sliding surfaces. The minimum surface temperature recorded when the first thermogranules were seen was about 342°C, but the flash temperature at this point of contact was much higher than the recorded bulk temperature as postulated by Anderson [15]. EDAX analysis showed that these thermogranules were composed of elements of high melting temperatures such as silica, iron, and titanium (Table 3). Melting point of iron, silica, and titanium is about 1538°C, 1414°C, and 1670°C respectively. Whereas, other elements in the composition, which have boiling temperature such as Mg, Ca, and K have evaporated to the atmosphere. Boiling point of Mg, Ca, and K is about 650°C, 842°C, and 63.7°C respectively, which is lower than the melting point of titanium. As the braking progressed, these metal droplets rolled between the two sliding surfaces and finally formed granule shapes of metal particles.

Table 3 Element composition in thermogranules (%)

Element	**Sample B3**	**Sample C2**	**Sample D1**	**Sample E1**
Si	2.914	2.582	2.369	2.123
Ti	1.540	1.150	1.107	1.141
Fe	95.546	96.268	96.524	96.736
Total	100.000	100.000	100.000	100.000

Micrographs showed that the generation of thermogranules were first seen during braking time of 9 minutes when the applied load was 200 N (Figure 3). As the load increased, the accumulated heat also increased and thus the surface temperature. Therefore, thermal granules were generated earlier at braking times of 6 minutes and 3 minutes when the applied load was increased to 400 N and 600 N, respectively (Figure 4). In this study, it was observed that the thermal granules were located at a higher position on the wear surfaces and thus became the contact area as sliding progressed. With subsequent braking times, thermal granules formed the contact area, which would be subjected to high pressures as they have to carry high loads. At the same time, the temperature rise at the contact area introduced thermal stresses which could superimpose onto the mechanical stresses [16]. As sliding continued, the thermogranules were compacted and smeared on the wear surface (Figure 5). These repeated phenomena during braking caused the generation of thermomicrocrack at the contact areas. With subsequent braking, the microcracks grew, propagated and finally joined together, forming multiple thermomicrocracks. Figures 6 and 7 show the formation of multiple thermomicrocracks when braking time was increased to 12

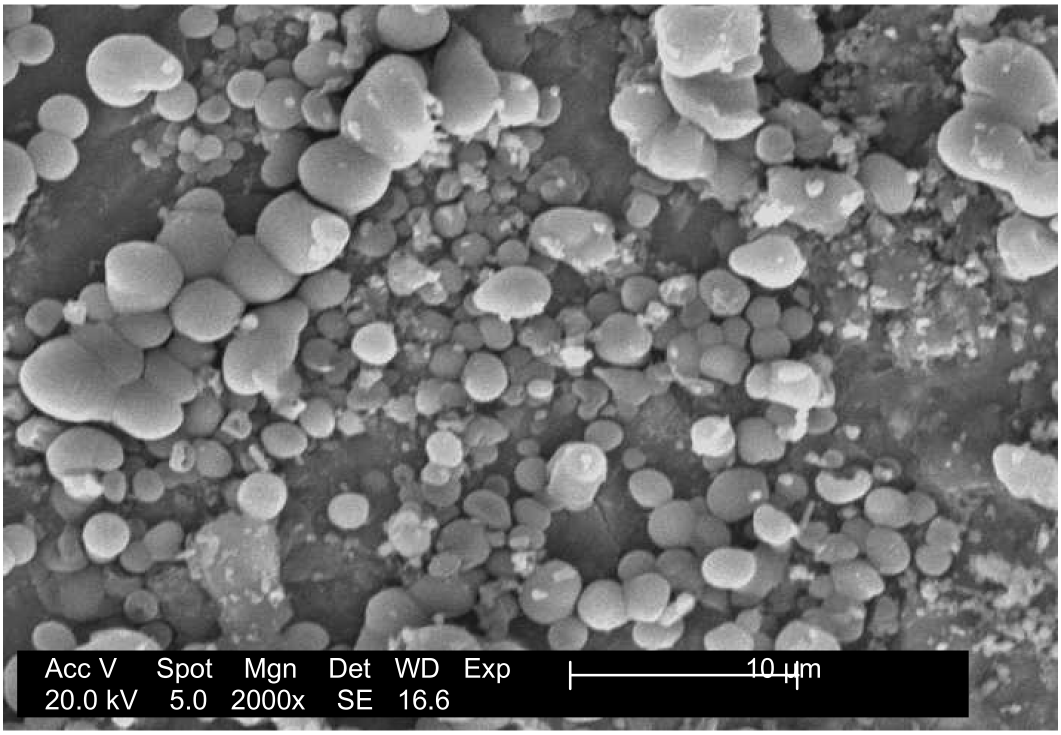

Figure 3 Formation of thermal granules. Applied load 200 N and braking time 9 minutes

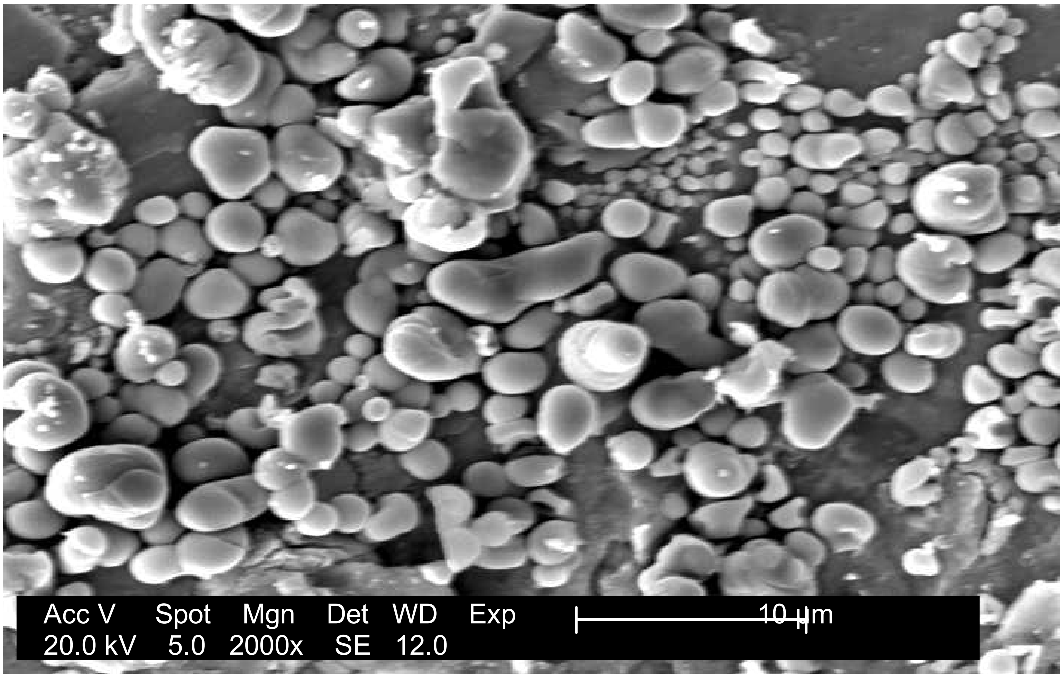

Figure 4 Formation of thermal granules. Applied load 400 N and braking time 6 minutes

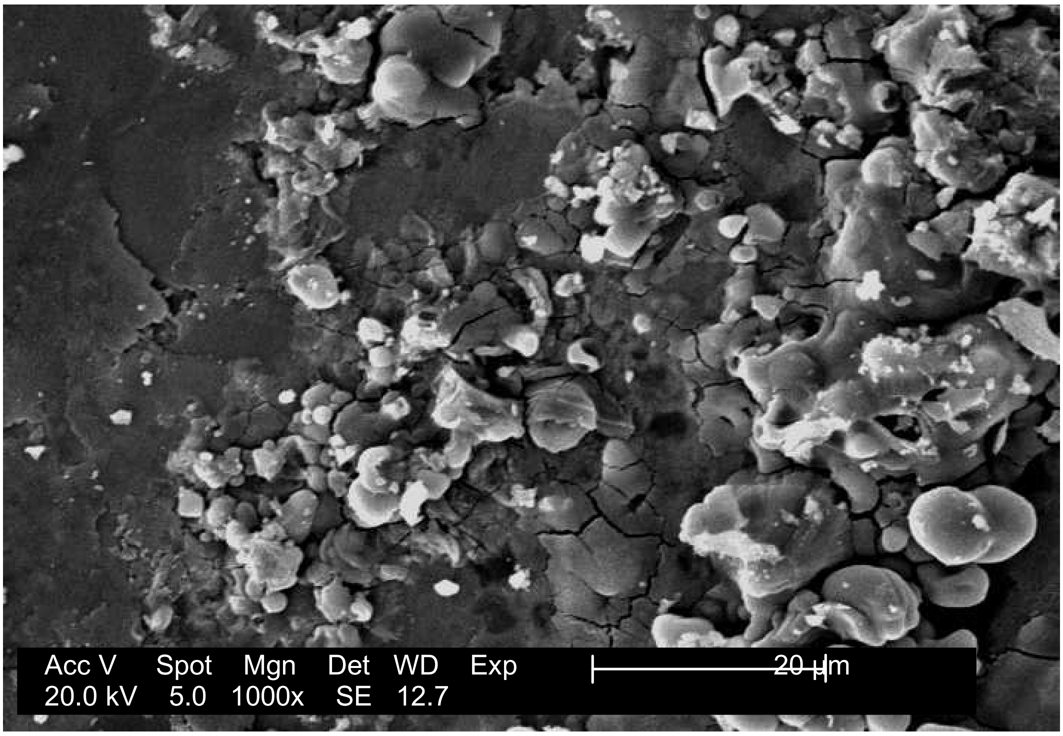

Figure 5 Formation of thermal layers. Applied load 600 N and braking time 6 minutes

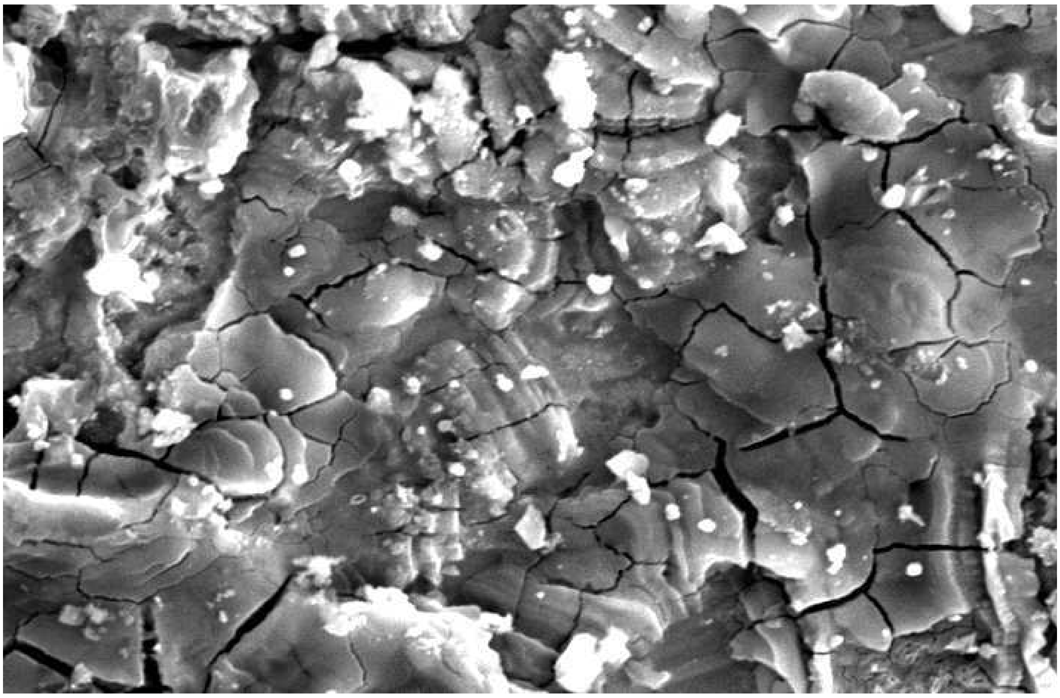

Figure 6 Formation of multiple thermomicrocracks. Applied load 200 N and braking time 9 minutes

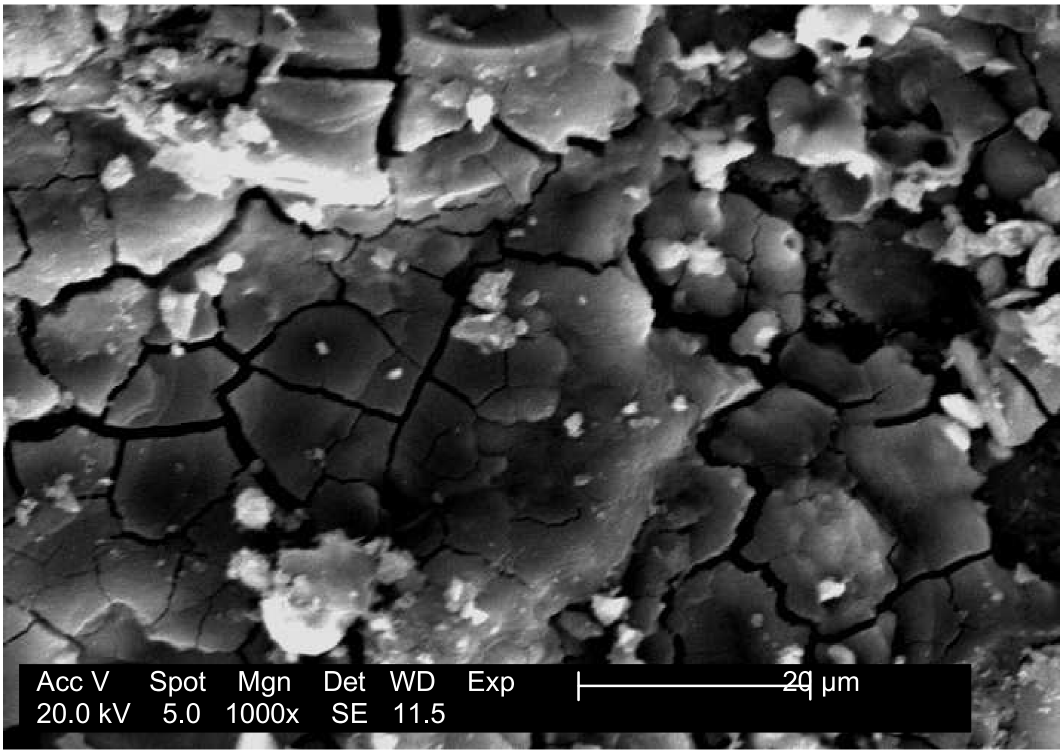

Figure 7 Formation of multiple thermal microcracks. Applied load 600 N and braking time 6 minutes

and 15 minutes, respectively. During this braking, the maximum surface temperature recorded by NiCr-Ni thermocouples embedded 5 mm beneath the sliding surface was 516°C.

Thermomicrocracks were observed to operate both in intermittent and continuous braking modes. In the intermittent braking, it was discovered that thermomicrocracks started to generate at a braking time of 800 seconds (Figure 8). This figure shows that the formation of thermomicrocrack patches was at the highest point of contact. The contact temperature at this time could reach the melting points of materials, resulting in high thermal stresses and subsequently developing microcracks in the brake pads. In this study, EDAX analysis showed that only elements of high melting points were left in the composition of thermomicrocrack patches, such as titanium, silica, and iron. With an increase in braking time, it was observed that the area of contact has grown with the generation of multiple thermomicrocracks, as shown in Figure 9. When the test was conducted on another model of sample, the same phenomenon was also observed (Figure 10, 11). Figure 12 shows the appearance of the wear surface after some of the melted elements had evaporated to the atmosphere. EDAX analysis also showed that this wear surface was only composed of high melting elements such as titanium, iron, and silica. From this result, it was postulated that the low melting

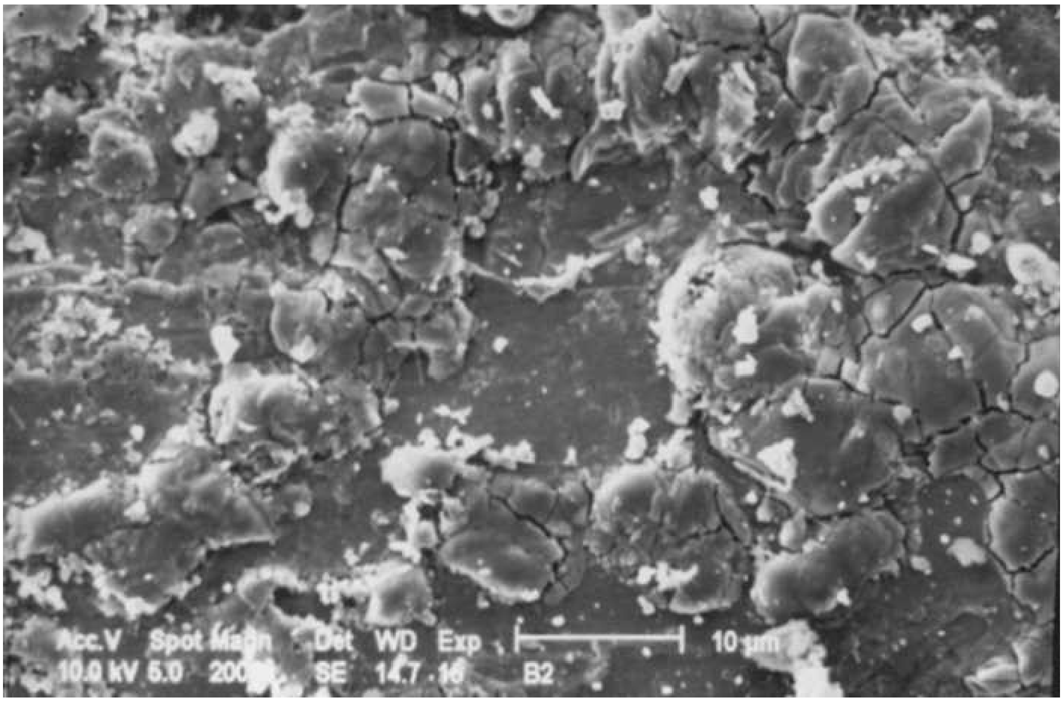

Figure 8 Thermomicrocrack generated during intermittent braking. Applied load 600 N and braking time 800 seconds

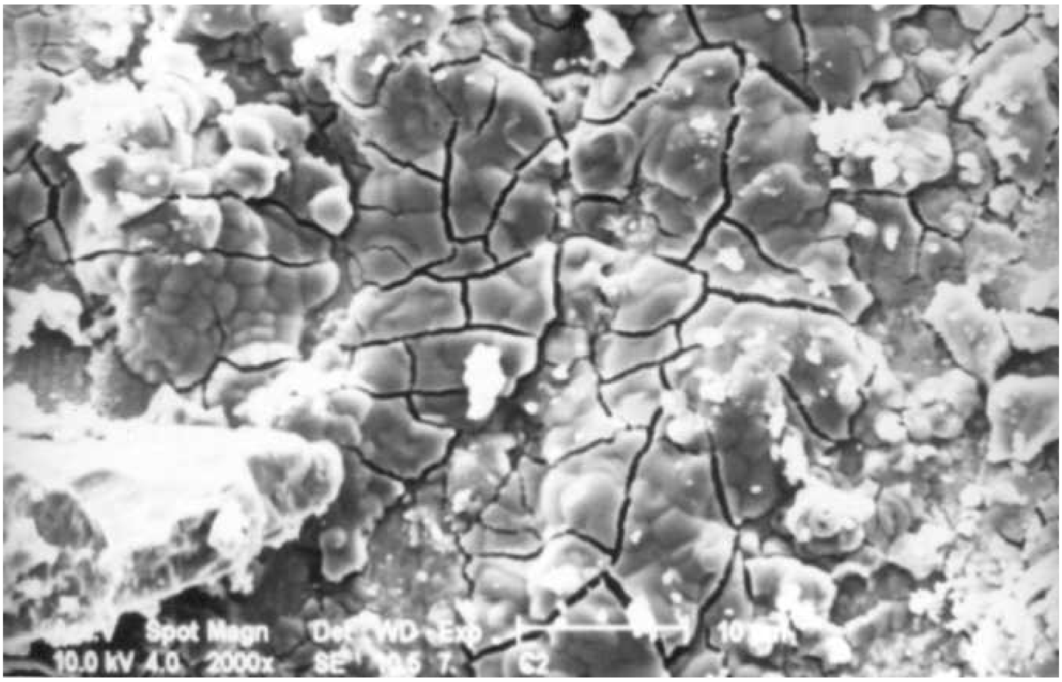

Figure 9 Formation of thermomicrocracks. Applied load 600 N and braking time 1,600 seconds

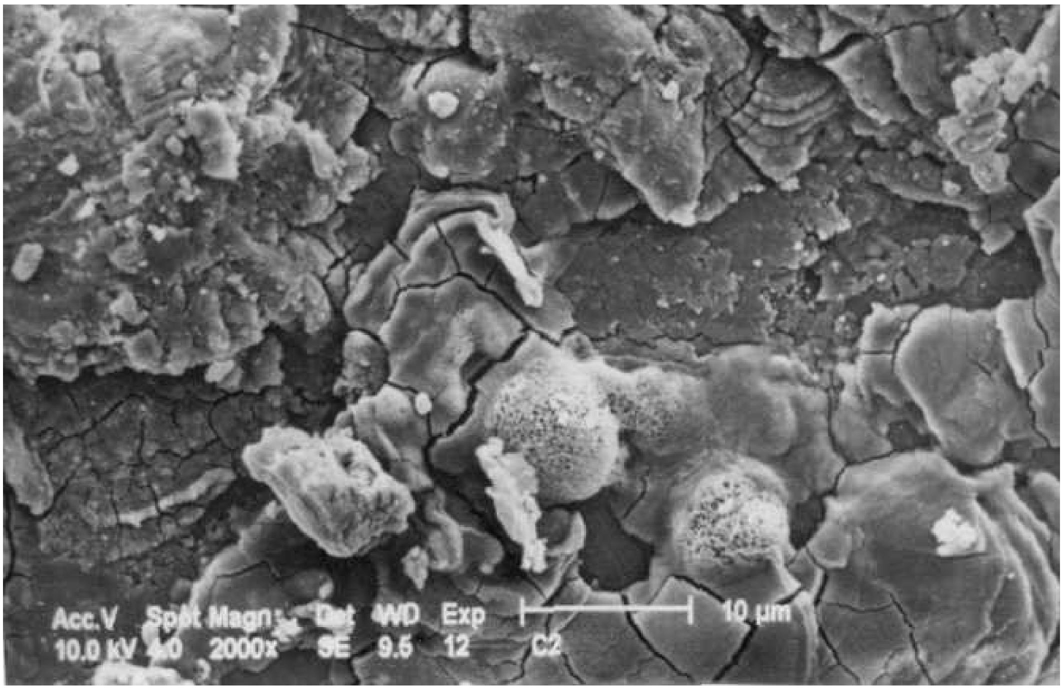

Figure 10 Thermomicrocrack generated during intermittent braking. Applied load 600 N and braking time 800 seconds

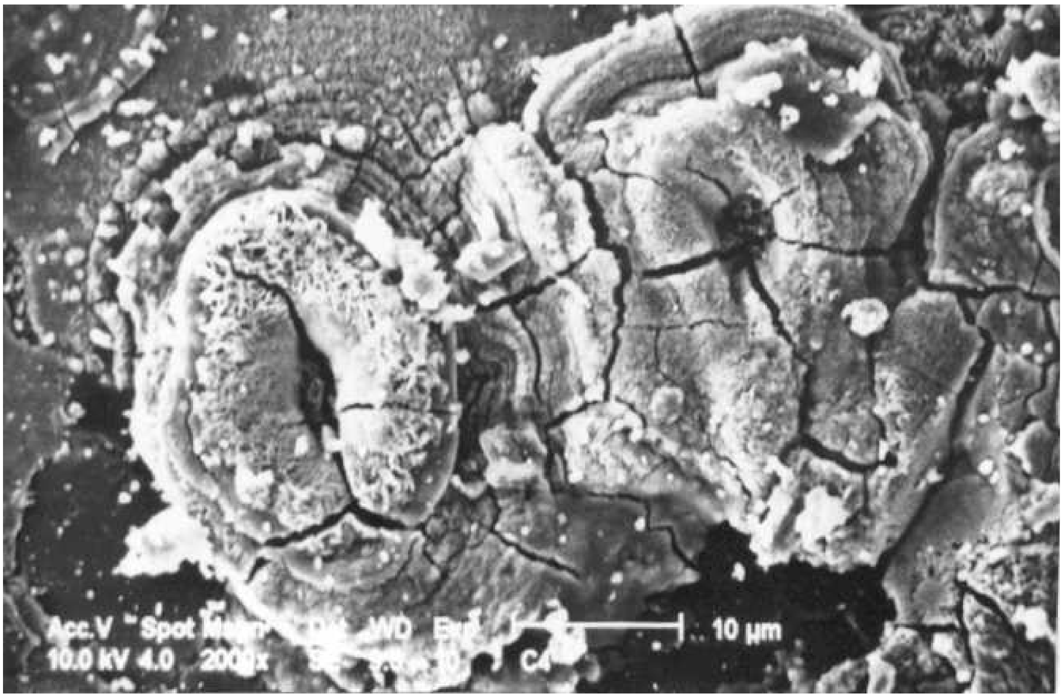

Figure 11 Thermomicrocrack. Applied load 600 N and braking time 1,600 seconds

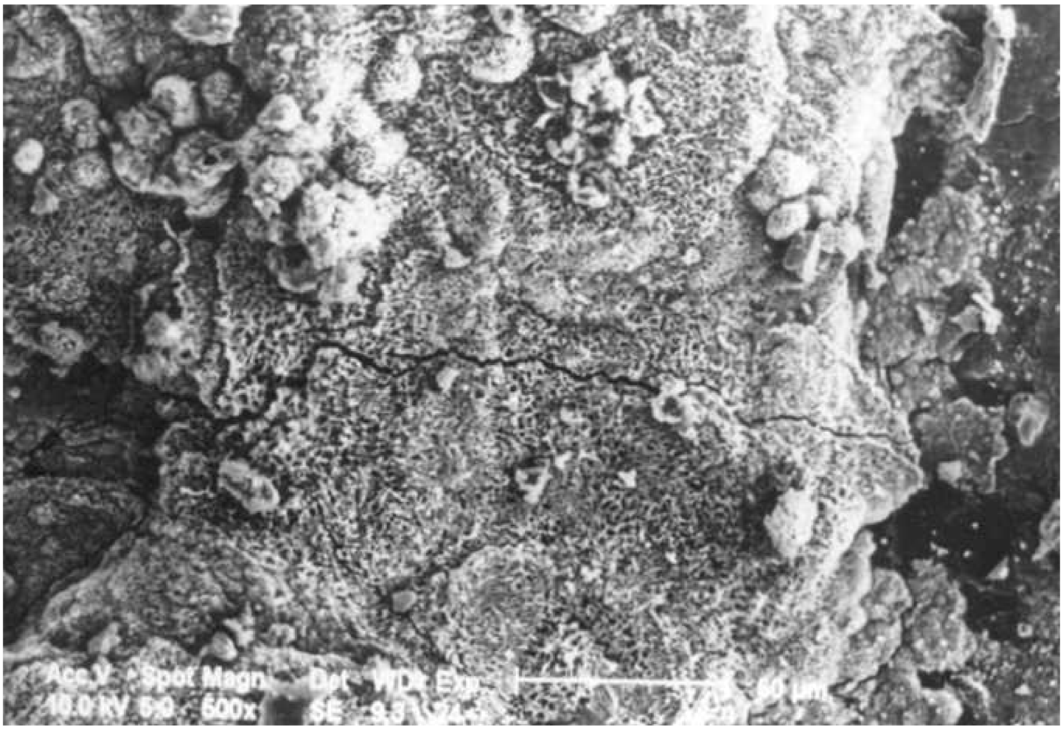

Figure 12 Micrograph shows the wear surface after composition have evaporated. Applied load 600 N and braking time 800 seconds

elements such as Mg, Ca, and K had evaporated to the atmosphere, leaving the appearance as shown in Figure 12.

In the continuous braking mode, the thermomicrocracks were first seen during braking time of 12 minutes and at the applied load of 200 N. As a result of temperature rise upon the increase in braking times or applied loads, thermomicrocracks were generated at an earlier braking time of 9 minutes (Figure 13). With subsequent braking, the microcracks grew, propagated and finally joined each other to form multiple microcracks which could cause the generation of wear particles (Figure 14).

In this study, the minimum surface temperature recorded when the first thermomicrocracks were seen was about 465°C. However, the flash temperature at this point of contact was found to be much higher than the recorded bulk temperature as reported by Anderson [15], where the flash temperature could reach between 1,000 to 1,125°C, when the speed was more than 5 m/s. In this study, the speed of the disc was kept constant at 11 m/s throughout the braking test, both in the intermittent and continuous braking modes. EDAX analysis showed that these wear particles which were generated at higher temperatures were composed of elements of high melting temperatures such as silica, iron, and titanium (Table 4). Melting point of iron, silica, and titanium is about 1539°C, 1414°C, and 1670°C respectively. Thus, we can assume

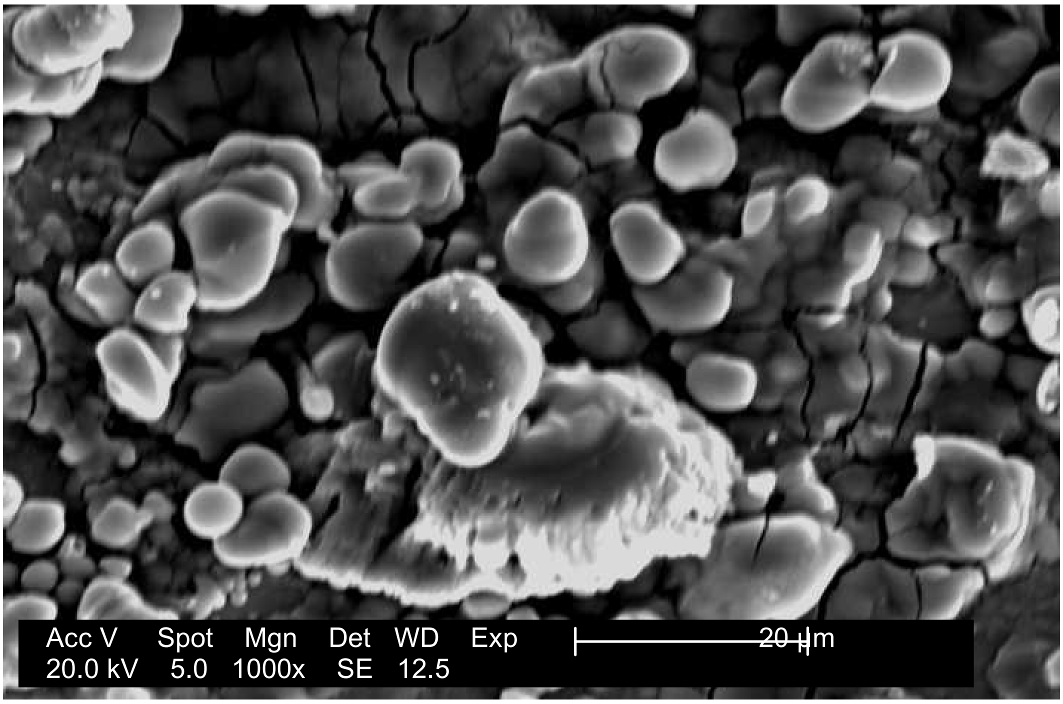

Figure 13 Thermomicrocrack. Applied load 400 N and braking time of 9 minutes

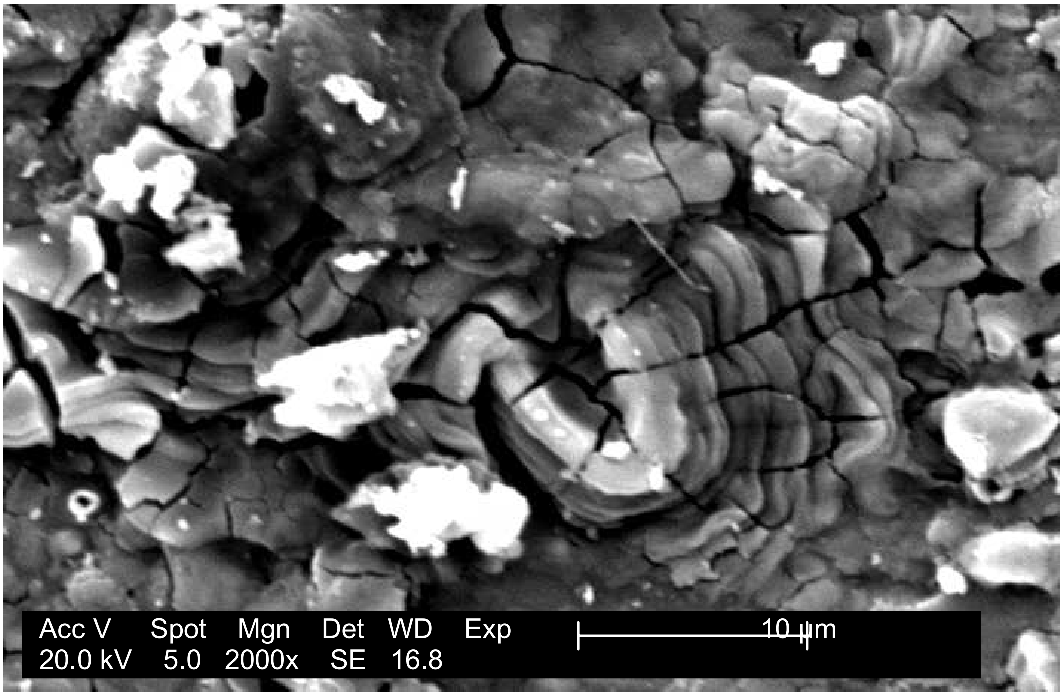

Figure 14 Micrograph shows the generation of wear particles. Applied load 400 N and braking time 15 minutes

Table 4 Element composition in thermomicrocracks (%)

Element	Sample B3	Sample B5	Sample C3	Sample C4	Sample C5
Si	1.202	0.800	1.38	1.269	1.666
Ti	0.460	0.519	-	0.787	1.141
Fe	98.338	98.680	98.62	97.944	97.193
Total	100.000	100.000	100.00	100.000	100.000

that the flash temperature at the point of contact must be higher than 1670°C, the melting point of titanium. At this high flash temperature, other elements in the composition which have low boiling temperatures such as Mg, Ca, and K had evaporated to the atmosphere. Boiling temperature of Mg, Ca, and K is about 650°C, 852°C, and 63.7°C respectively.

Microstructural examination of the subsurface revealed that themomicrocracks penetrated into the bulk material. This observation supports the postulation on the generation of thermomicrocracks on the lining materials during braking. Figure 15 shows the initiation of themomicrocracks on the subsurface under the applied load of

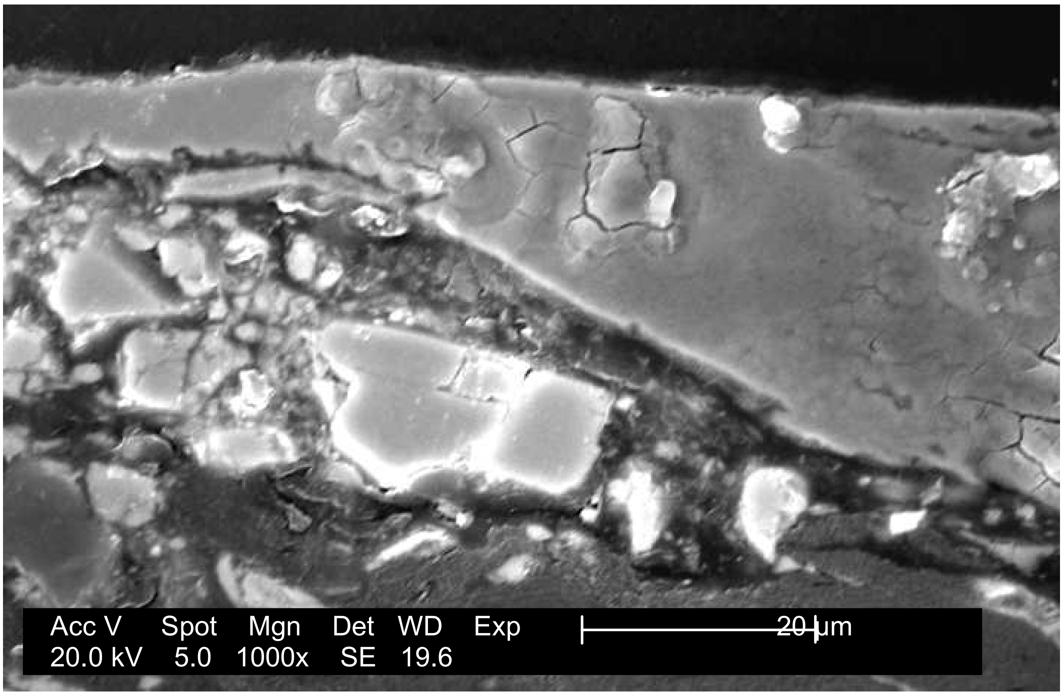

Figure 15 Early stage of thermomicrocracks generation in the subsurface. Applied load 400 N and braking time of 9 minutes

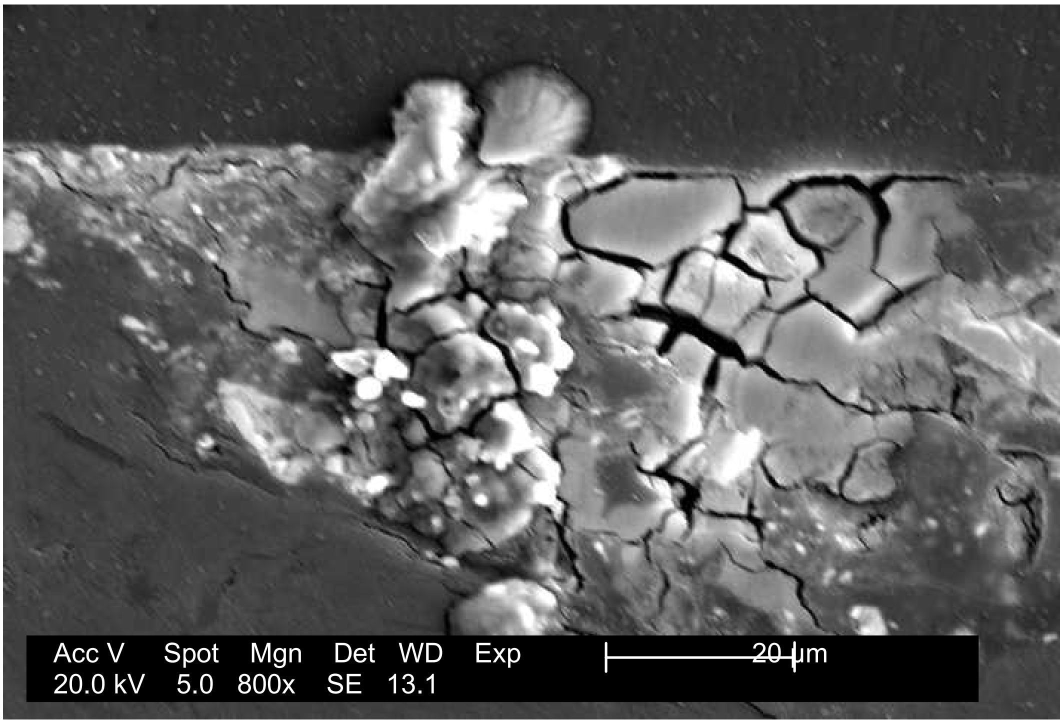

Figure 16 Multiple thermomicrocracks. Applied load 400 N and braking time 9 minutes

400 N and braking time of 6 minutes. When braking time was increased to 9 minutes, thermomicrocracks grew and propagated to the surface (Figure 16). From microstructural study, it may be concluded that thermoinstability during braking is influenced by the applied loads, braking times, and mode of braking.

4.0 CONCLUSIONS

Thermoinstability mechanism is found to operate in the process of braking. This mechanism is found with the following sequences; (i) formation of thermogranules, (ii) smearing and formation of thermo patches, (iii) generation of thermomicrocracks, and (iv) growth and propagation of thermomicrocracks. The process of thermoinstability generation depends on applied loads, braking times as well as braking modes. It was also observed that the generation of thermoinstabilitiy started earlier (first braking) when the applied load was increased to 600 N. The microstructural examination of the surface further strengthened the postulation on the generation and propagation of thermomicrocracks.

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