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Development and Characterization of Green Automotive Brakepads from Waste Shells of Giant African Snail (*Achatina achatina* L.)

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Abstract

In this study, waste shells of African giant snail (*Achatina achatina* L.) were explored as candidates for asbestos-free non-carcinogenic brakepads. The results obtained showed that the density, brinell hardness and compressive strength of the snail shell (SS) brake pads were superior to the commercial sample used for comparison. These properties were found to decrease with increase in particle size, following a negative index power law model after the order of the Hall-Petch equation. However, the liquid absorption characteristics increased with increase in particle size and its model followed a positive index power law due to the pores in the matrix. On the other hand, the thermal conductivity showed no significant change with variation in particle size. The SS-based brake pad exhibited better frictional grip at the rubbing interfaces compared to the commercial brake pad sample. From the frictional results obtained, the commercial brake pad can be rated as Edge-Code-D whereas the frictional rating for the SS-based brake pad with different particle sizes are Edge-Code-E (500 μ m and 250 μ m), Edge-Code-F (375 μ m), Edge-Code-G (125 μ m) and Edge-Code-H (90 μ m). The wear rates and wear areas of the developed SS-based brake pads were inferior to the commercial sample but can be improved by impregnating the matrix with more iron fillings to enhance the poor thermal conductivity and hence wear characteristics.

Keywords: Green brake pads, giant African snail shells, Hall-Petch equation, grain size, power law model

1. Introduction

The phasing out of asbestos-based materials for engineering applications due to their carcinogenic impact on human and animal health has prompted researches for “greener” alternatives. In tribological parlance, engineering materials that have negligible negative impacts on human and animal health, as well as, the environment are considered to be “green” materials, and hence the need to explore biodegradable materials. Locally available biodegradable materials such as, Rice husk and rice straw [1], palm kernel shells [2], coconut shells [3], periwinkle shells [4], [5] and saw-dust [6], have been explored with varying performance levels.

Mutuk and Gurbuz [7] investigated pure titanium samples of particle sizes $\leq 30\mu\text{m}$, $\leq 43\mu\text{m}$, and $\leq 150\mu\text{m}$ sintered at 1100°C for 120min with a view to ascertain the role of particle size on the density, hardness, wear resistance and microstructural properties. In the study, the sample with lowest particle size $\leq 30\mu\text{m}$ showed the best mechanical properties. Their wear rate and SEM results indicated that the superior mechanical properties was attributable to good bonding and strong neck formation between the particles with smallest size. These results were corroborated by Ossia et al. [3] showing that particulate grain size affected the physico-mechanical properties of organic brake pads.

In the search for green biodegradable alternatives to the carcinogenic asbestos-based commercial brake pads, waste African giant snail (*Achatina achatina* L.) shells are yet to be explored. Besides the opportunity to mop-up this waste organic material, its conversion to biodegradable brake pad composites will offer good economic and environmental competitiveness. It is this potential that the present study seeks to explore.

2. Materials and Methods

2.1 Materials

The base material for the green brake pad is the waste African giant snail shell, which were obtained from a refuse dump at the local Choba main market, Port Harcourt, Nigeria. Typical waste shells of the African giant snail are shown in Figure 1.

Figure 1: Waste shells of African Giant Snail in (a) gathered, (b) crushed, (c) grinded conditions

The chemical reagents applied in formulating the SS-based brake pads matrix are: (a) milky phenol formaldehyde (99% purity) (*Dachy polymer, Taiwan*) used as resin, (b) whitish calcium carbonate, CaCO_3 , (99.5% purity) (*Skyline chemical, USA*) used as filler, (c) colourless methyl-ethyl ketone peroxide – MEKP (99% purity) (*Akzonobel, China*) used as accelerator, (d) purple cobalt naphanate (99% purity) (*Akzonobel, China*) used as catalyst, (e) carbon black (99.9% purity) (*Loba chemie, India*) used as friction modifier, and (f) iron fillings used to boost thermal conductivity.

Others include: (a) distilled water, (b) Engine oil (SAE 40 Oil), brake pad mould fabricated from carbon steel plate, Vernier caliper, weighing balance, hardness tester, crushing machine, Sieves of different sizes, milling machine, and electric oven.

2.2 Methods

2.2.1 Development Process

The procedure and processes used in the development of the sample brake pads is similar to that used by Ossia et al [3] in the production of brake pad samples from waste coconut (*cocos nucifera L.*) shells as in Figure 2.

Figure 2: SS-based brake pad sample development process (Ossia et al., [3])

(a) Gathering / Washing / Cleaning: The waste snail shells was gathered at Choba market, Port Harcourt, Nigeria to get the required quantity. The snail shells was thoroughly washed and cleaned to remove dirt and bad smell.

(b) Drying / Crushing / Grinding: The snail shells were dried in sunlight for 3days to reduce their moisture content; then the snails where crushed into smaller pieces and grinded in the laboratory using a grinding machine.

(c) Sieving: The grinded snail shells were separated into different grain sizes (90µm, 125µm, 250µm, 300µm and 500µm); and separated into different bags with their grain size labels. This process involved arranging the sieves in descending order, applying a quantity of the grinded snail shell in the largest sieve size at the top. The top sieve is covered with the sieve pan cover and shaking vigorously for 10min to separate the grinded snail shells at the top to different particle sizes; the quantity left in every sieve size at the end of the 10min is put in a pan with its label.

(d) Moulding / Mixing: The mould was designed with solidworks software and fabricated in University Engineering Workshop. The process involves cutting into shape and welding. The formulation from Table 1 was used; a clean bowl was used in mixing the formulation which was stirred thoroughly to have a homogenous mixture. The binder was added last to avoid the mixture getting hard before leaving the bowl. The mixture was poured into the mould and rammed so the mixture fully occupies the mould.

(e) Setting / Curing: The laboratory brake pad was cured in an electric oven (*Model: GE30*) at a temperature of 120°C for 2 hours.

(f) Extraction: Extraction was done after leaving the newly made brake pad for 1 day to cool and become very hard. The grease applied before the mixture was poured into the mould helps in separating the sample from the mould.

(g) Machining (milling): The extracted brake pad sample is then machined to shape using a carrot stone and a cutting disk with a spindle speed of 288 rpm. The SS-based brake pad samples thus developed were then shaped to size using the milling machine (*Model: HURE SA-PU771, France*).

Table 1: Material Formulation for the snail shell brake pad sample

s/N	Materials	Composition (wt %)
1	Snail shell	53.9
2	Phenol formadyhde (resin)	25
3	Calcium carbonate (CaCO ₃) (filler)	11.7
4	Carbon black (friction modifier)	0.5
5	Metylethyl ketone (accelerator)	2.8
6	Cobalt nephtanate (catalyst)	2.1
7	Iron fillings(abrasive)	5.0

2.2.2 Evaluation Tests

The physicomechanical tests involving oil (SAE 40) absorption. Water absorption, density, Brinell hardness, compressive strength and thermal conductivity properties tests were performed on the SS-based brake pad samples following procedures adopted from Ossia et al [3].

Friction and wear tests were performed using Anton Paar GmbH TRB3 Tribometer (version 6.1.19) with ø6mm stainless steel ball-on-brakepad disc samples in dry sliding contact. All the tribological tests were performed at ambient temperature and humidity conditions of 29°C and 55%, respectively. The brake pad samples were turned into a rotating disc sliding against a

stationary ball loaded with 8N at 10cm/s sliding speed in accordance with ASTM procedure [8]. The friction histories of the interface were recorded, as well as, the wear scar area and wear rates.

3. Results and Discussion

3.1 Absorption Test

Figure 3, Absorption in Oil and water for SS-based Brakepads with different particle grain sizes

From Figure 3 it was shown that oil absorption of the SS-based brake pad sample increased with increasing grain size. This can be attributed to better bonding between the smaller grain sizes and the binder. When compared with the commercial brake pad, all the developed samples did better. The sample brake pad will do better than the commercial brake pad when there is hydraulic oil leakage.

Also, the water absorption of the sample brake pad increased with increasing grain size. This can be attributed to better bonding between the smaller grain sizes and the binder. When compared with the commercial brake pad the $90\mu\text{m}$ and $125\mu\text{m}$ sample did better than the commercial brake pad (with 1.2% absorption in water and 6.1% absorption in SAE40 Oil). The sample brake pad will do better than the commercial brake pad if used in a wet environment, for instance, when an automobile goes through a flooded road.

The absorption variation with respect to particle grain size corroborates conclusions of previous studies [2], [9], [10], [4], [3]. The present results show that the absorption property of the control (commercial) brake pad in SAE40 oil was poor compared to those of the SS-based brake pad.

3.2 Density

Figure 4 shows a variation of the density of the SS-based brakepad with particle grain size. The decrease in density can be attributed to the increase in pore size derived from increased aggregate particle size. The 90 μm has the highest density (1.74g/cm³) which is as a result of closer packing of snail shell aggregate creating more homogeneity in the entire phase of the composite body. Similar decrease in brake pad density with increase in particle grain size had been reported by Yawas et. al. [6] who used periwinkle shells.

Figure 4, Density of SS-based brake pad for different particle grain sizes

From Figure 4, the densities of all SS-based brake pad samples were lower than the control brake pad density (2.18g/cm³). This makes the SS-based brake pad lighter and brings about a reduction in the mass of the automotive braking assembly.

3.4 Hardness (Brinell)

The Figure 5 shows that the hardness of sample brake pad varies with increase in grain size. The 90 μm sample has the highest hardness value of 49BHN. A sharp drop in hardness was observed in the samples with higher grain sizes (125 μm), (250 μm), (375 μm) and (500 μm). The high hardness for the 90 μm particle size sample is attributable to the increase in particle surface area which resulted to increased bonding with the polyester resin. This corroborates the results of Yawas et. al. [4] who observed a similar trend with periwinkle shells. It can be observed from Figure 4 that the hardness of the samples developed from 90 μm and 125 μm particle grain sizes (49BHN and 41BHN, respectively) were greater than the hardness of the control brake pad (39BHN).

Figure 5: Hardness of experimental brake pads compared with commercial brake pad

3.5 Compressive strength

Figure 6 shows the variation of compressive strength with grain size of the sample brake pad. From the results obtained it was observed that the compressive strength increases with decrease in grain size of the specimen. The 90μm sample had the highest compressive strength (3.77MPa), which was greater than that of the control brake pad (2.85MPa). The gradual decrease in compressive strength as the aggregate increases can be attributed to the decreasing surface area and pore packaging capability of the snail particles in the phenol formaldehyde resin.

Hence, compressive strength increases as aggregate size of the snail shell decreases. During braking, the brakes are exposed to continuous compressive force and the result show that the 90μm sample will do well under such conditions. The observed trend in the relationship between compressive strength and grain size is corroborated by the conclusions of Yawas et al [4] and Jaya et al [6].

Figure 6: Compressive Strength of the SS-based brake pads with different particle grain sizes

3.6 Thermal conductivity Test

Thermal conductivity is an important consideration in the design of a brake pad. Figure 7 shows how the sample brake pad thermal conductivity compares to that of the commercial brake pad. The commercial brake pad had thermal conductivity (2.02Wm/k) superior to the sample brake pad (1.81 - 1.84Wm/k). The thermal conductivity appears not to be significantly affected by the increase in the grain size. The thermal conductivity of the sample brake pad can be improved by introducing particles of strong (hard) metallic conductors in its formulation.

Figure 7: Thermal conductivity of SS-based brakepads with different particle grain sizes

3.7 Modeling green brake pads Mechanical Properties variation with SS-Particle size

To model the influence of snail shell particle size on the mechanical properties of the developed green brake pad, a modified form of the classic Hall-Petch equation was adopted. Morris [11] proposed an inverse proportionality relationship with respect to the square root of the grain size diameter (d) and material constants (K_y and σ_o) to explain the influence of grain size on the mechanical properties (σ_y) of metals. Morris' model is a form of the classic Hall-Petch equation and is shown in equation (1).

$$\sigma_y = \sigma_o + \frac{k_y}{d^{1/2}} \quad (1)$$

Morris [12] reported that in nanometals the increase of mechanical properties with respect to decrease in grain size (d) continues to a peak at about 20nm grain size (d) beyond which a fall in properties prevails. Hence, two regimes of property variation were reported, namely: regime I for $0 \leq d \leq 20\text{nm}$ (inverse Hall-Petch effect regime where the property decreases with decreasing grain size); and regime II for $d \geq 20\text{nm}$ (Hall-Petch effect regime where the property decreases with increasing grain size).

Other exponents apart from $x = 1/2$ have been reported for the Hall-Petch model. Different x -exponents in the range $0 < x \leq 1$ have been reported based on experiments. Dunstan and Bushby [13] obtained $x = 1$ for FCC and BCC metals and ceramics in the compression testing of micropillars by using grain size as bulk micropillar diameters (d) which was corroborated by Li et

al [14]. Agraie-Khafri et al. [15] reported $x = 0.66$ for hot rolled AISI 300 stainless steel in uniaxial tensile tests at 0.2% strain..

In this study, the mechanical properties, y_p , of the sample brake pad were modeled by power law relationship after the order of a modified Hall-Petch equation (2).

$$y_p = \frac{K_p}{X^a} \quad (2)$$

where; X - Particle size value (μm) equivalent to Hall-Petch grain size (d);
 k_p - particle size constant;
 a - particle size index equivalent to Hall-Petch grain exponent ($1/2$);

The mechanical property results obtained in Figures 2 to 5 were modeled by power law for best-fit after 100-iterations using SigmaPlot-8 software. The models obtained for the mechanical properties, their R-value and error estimate are summarized in Table 2.

Table 2: Models of mechanical properties of SS brake pad samples as functions of particle size

s/N	Mechanical Property	Mathematical Model	Coefficient of determination R^2	Standard Error of Estimation ϵ	p-value
1	Oil Absorption, A_o	$A_o = 0.03077X^{0.6284}$	0.9939	0.0383	0.0002
2	Water Absorption, A_w	$A_w = 0.06516X^{0.5718}$	0.9094	0.2248	0.0119
3	Density, ρ	$\rho = \frac{3.5962}{X^{0.1633}}$	0.9889	0.0217	0.0005
4	Harness, BHN	$BHN = \frac{191.6881}{X^{0.3092}}$	0.9778	1.4335	0.0041
5	Compressive strength, σ_c	$\sigma_c = \frac{10.7353}{X^{0.23803}}$	0.9709	0.1039	0.0021
6	Thermal conductivity, k	$k = 1.7416X^{0.008156}$	0.7668	0.0068	0.0516

The nonlinear regression of thermal conductivity with particle grain size is rather weak because of the lower coefficient of determination $R^2 = 0.7668$.

It is instructive to observe that all mechanical property models in Table 2 are similar, following a power law with a positive or negative particle size index, indicating similar generating mechanism. It showed positive particle size indices for oil absorption, water absorption and thermal conductivity (flow processes) and negative particle size indices for density, hardness and compressive strength (non-flow processes). These properties are attributable to the roles of pores in the composite matrix. The higher the matrix particle size, the higher the pore size and distribution that enhance absorption as the pores are being filled in the soaking (absorption) medium. But the corollary is true for other mechanical properties, since the higher pores associated

with higher matrix particle sizes become crack nucleation sites in the course of loading before failure in hardness or compression test. Hence, higher particle sizes become associated with lower hardness and compressive strength. Obviously, for a fixed volume of brakepad matrix the sample with higher particle size, hence higher pores sizes and distribution will exhibit less mass, and hence less density which corroborates the model result. This explains the results earlier obtained by Dagwa et al [2], Yawas et al [4], Zykova et al [9], Ameh et al [10] and Jaya et al [6].

3.8 Tribological Performance Characterization

3.8.1 Friction characterization of the Ball-on-Disc sliding contact

(a) Friction history

The friction history, which is a measure of kinetic friction trace of all the developed brake pad samples showed 2 friction regimes, namely: the transient and steady state regimes. The transient regime is characterized by friction rise from zero (or minimum value) to the onset of steady state value. From Figure 8 to Figure 13, when the steady state value is attained the kinetic friction remains at this value till the end of the sliding contact. So, the friction signatures in Figure 8 to Figure 13 can be observed to follow through a minimum, average and maximum friction values for every friction trace. While the friction mechanism in the transient regime could be explained by the surface roughness (asperity interlock) friction theory [16], that of the steady state regime can be explained by the simple adhesion friction theory due to the filling of the matrix pores close to the interface by initial wear metal transfer.

Figure 8, Friction history of SS-based Brake pad sample with 90μm particle size

Figure 9, Friction history of SS-based Brake pad sample with 125 μ m particle size

Figure 10, Friction history of SS-based Brake pad sample with 250 μ m particle size

Figure 11, Friction history of SS-based Brake pad sample with 375 μ m particle size

Figure 12, Friction history of SS-based Brake pad sample with 500 μ m particle size

Figure 13, Friction history of the control brake pad sample

(b) Average friction Coefficient

Figure 14 shows the average friction coefficient for the sliding contact of a steel ball sliding on the brake pad disc in a 1010 secs test. The results showed increase in friction coefficient with increase in particle grain size. The friction coefficient of the commercial sample was less than that of the highest grain size sample, that is, the 500 μ m grain size sample. This result is in contrast with Yawas et al [4] result based on periwinkle shells, but corroborated that of Amaren et al [5] who studied the effect of periwinkle particle size on the wear of brake pad using full factorial experimental design. Amaren et al [5] obtained a negative main effect (-0.025) of periwinkle particle size on friction coefficient models for brake pads. Of all the 4 independent variables (load, speed, temperature, and particle size) used to model friction and wear in the study, particle size was the most significant (p-value 0.02777). This friction coefficient variation trend with respect to particle size was also observed by Sasaki [17] and Aigbodion et al. [18].

From the friction values in Figure 14 and based on the work of Blau [19] and SAE J866a [20] standards for friction identification of brake linings and brake blocks, the commercial brake pad can be rated as Edge Code-D whereas the 500 μ m sample is Edge-Coded-E, 375 μ m sample is Edge-Coded-F, 250 μ m sample is Edge-Coded-E, 125 μ m sample is Edge-Coded-G and 90 μ m sample is Edge-Coded-H. Finally, the frictional responses in Figure 14 suggest that the green brake pads offer better or more effective grip at the rubbing interface relative to the commercial brake pads. This frictional property improved with decreasing particle size.

The average friction coefficient μ_{ave} was modeled as equation (3).

$$\mu_{ave} = \frac{5.01326}{x^{0.4716}} \quad (3)$$

Figure 14, Average friction coefficient of SS-based brake pad samples with different grain sizes Where coefficient of determination $R^2 = 0.9533$, standard error of estimate = 0.0358, and p-value = 0.0043. It is obvious that as the particle size increases, the average friction coefficient decreases, hence corroborating Amaren et al [5] negative effect.

3.8.2 Wear Characterization of green brake pads using ball-on-disc sliding contacts

The wear rates and wear areas of the worn brake pads were observed to decrease with the increase in snail-shell granular particle size as in Figure 15. All SS-based brake pad samples exhibited higher wear rates and wear surface areas compared to the control brake pad. This is attributable to the poor thermal conductivity of the sample brake pads which made them thermally unstable during the friction heating of the rubbing contacts. This poor wear behavior can be compensated by impregnating the composite matrix of the sample brake pads with higher percentage of iron fillings to obtain better frictional grip with reduced wear rates and wear surface.

The wear area was modeled as equation (4).

$$W_{area} = 55.8769 - 0.01977x^{1.1469} \quad (4)$$

Where coefficient of determination $R^2 = 0.9828$, standard error of estimate = 1.6631 and p-value = 0.0172. Also, the wear rate model was obtained as equation (5).

$$W_{rate} = 250.717 - 1.859x^{0.6934} \quad (5)$$

Where coefficient of determination $R^2 = 0.9384$, standard error of estimate = 14.7525 and p-value = 0.0616. Comparing equation (4) and equation (5) with equation (1), it can be observed that wear rate and wear are models followed the classical Hall-Petch equation with negative particle

constants k_y and positive particle (grain) size indices since wear particle generating mechanism was by plastic flow due to crack propagation.

Figure 15, Wear characterization of SS-based brake pads with different particle grain sizes

Different scholars attempting to relate wear rates with particle size of specimens have obtained variant results in the recent past. Sevim and Eryurek [21] obtained results showing that wear resistance of non-heat treated steel was inversely proportional to the square root of the abrasive particle size by gravimetric measurement. This is at variance with the results of the present study due to the fact that Sevim and Eryurek [21] considered the particle size of the harder (abrasive) material while the present study focused on the particle size of the softer (abraded) material. Arora et al [22] investigated the influence of particle size and temperature on the wear properties of rutile-reinforced aluminum metal matrix composites. They obtained results for a 49N load on a pin-on-disc tribometer which indicated that finer particles (50–75 μm) exhibited wear resistances that are two orders greater than the corresponding results of composites with coarse particle sizes (106–125 μm). Santos et al [23] used dimensional change measurement of AISI 1020 steels with Alumina Al_2O_3 coatings of different particles sizes (92nm – 76.79 μm) at 10.2N load in the adhesive wear and 130N in abrasive wear mode. Their results showed a logarithmic rise of wear volume with respect to particle size which was more pronounced at nanoscale (<100nm); but for particle size > 10 μm there was little or no particle size effect on wear in both adhesive and abrasive modes.

A typical finished SS-based brake pad with 125 μ m particle size mounted on the back-plate ready for installation on a brake-disc is shown in Figure 16.

Figure 16: The finished SS-brake pad with 125 μ m particle grain size

4. Conclusion

Experimental evidence in the present study showed that the application of waste African snail shell as base material for brake pads has the potentials of a good replacement for the carcinogenic asbestos-based brake pads. The mechanical properties of the SS-based brake pads, such as density, brinell hardness and compressive strength decreased with increase in particle size, following a power law model with negative power exponent after the order of the Hall-Petch equation. However, the liquid absorption and thermal conductivity properties (flow processes) exhibited models with positive particle size indices. Whereas the absorption of the SS-based brake pads increased with increase in particle size due to the pores in the matrix which increased with particle size, the thermal conductivity showed lower variation with particle size. The SS-based brake pads exhibited better frictional grip at the rubbing interfaces compared to the commercial brake pad. However, the wear behavior was poor compared to the commercial sample. This poor wear behavior can be compensated by impregnating the composite matrix with higher percentage of iron fillings to improve its thermal conductivity and stability.

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Declarations

Ethical Approvals: Ethical approvals are not required for this research work.

Consent to Participate: Consent is hereby given by Authors for the Journal Editorial / Review Team to participate in the Manuscript Blind-Review Process prior to publication

Consent to Publish: Consent is hereby granted by the Authors for the Editorial Team and Publishers to proceed with the Publication of the Research Manuscript after acceptance

Authors Contribution: The research contained herein describes a green, non-carcinogenic, asbestos-free automotive brake pad derived from biodegradable organic composite of waste snail shells as an alternative to the asbestos-based brake pads. The lead / correspondence author conceptualized, supervised and implemented the research while the second (contributing) author performed the editing.

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Competing Interests: To the best of Authors knowledge, there is no conflict of interest or competing interest involved in this research

Availability of Data & materials: All data generated or analyzed during this study are included in this manuscript and its supplementary files.

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Figures

(a)

(b)

(c)

Figure 1

Waste shells of African Giant Snail in (a) gathered, (b) crushed, (c) grinded conditions

Figure 2

SS-based brake pad sample development process (Ossia et al., [3])

Figure 3

SS-based brake pad sample development process (Ossia et al., [3])

Figure 4

Density of SS-based brake pad for different particle grain sizes

Figure 5

Hardness of experimental brake pads compared with commercial brake pad

Figure 6

Compressive Strength of the SS-based brake pads with different particle grain sizes

Figure 7

Thermal conductivity of SS-based brakepads with different particle grain sizes

Figure 8

Friction history of SS-based Brake pad sample with 90μm particle size

Figure 9

Friction history of SS-based Brake pad sample with 125μm particle size

Figure 10

Friction history of SS-based Brake pad sample with 250μm particle size

Figure 11

Friction history of SS-based Brake pad sample with 375μm particle size

Figure 12

Friction history of SS-based Brake pad sample with 500μm particle size

Figure 13

Friction history of the control brake pad sample

Figure 14

Average friction coefficient of SS-based brake pad samples with different grain sizes Where coefficient of determination $R^2 = 0.9533$, standard error of estimate = 0.0358, and p-value = 0.0043. It is obvious that as the particle size increases, the average friction coefficient decreases, hence corroborating Amaren et al [5] negative effect.

Figure 15

Wear characterization of SS-based brake pads with different particle grain sizes

Figure 16

The finished SS-brake pad with 125µm particle grain size