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Thermal Behaviour of Oyster Shell as an Abrasive for Industrial Grinding Wheel

Elenwo Onyinyechi Pauline[1], Ugwuagbo Kingsley Kamsiyochukwu[1], Uchegbulam Ifeanyi[2]*
[1]*Physics Department, Faculty of Science, University of Port Harcourt, Choba PMB 5323, Nigeria*
[2]*Production Technology, School of Science Laboratory Technology, University of Port Harcourt, Choba PMB 5323, Nigeria*
**Corresponding Author*

Abstract: Demand for products with excellent dimensional accuracy, structural stability and surface integrity makes hard and brittle abrasives for grinding wheels to be highly sought for which becomes more attractive when recovered from wastes for cost reduction and environmental sustainability. It is challenging to control generated heat during grinding operations, hence, thermo physical stability of grinding wheels made from Oyster shell abrasives(OSA)is hereby studied. Aimed at producing wheels with potentials to compete favorably with those made from mineral abrasives associated with high cost of production, health and environmentally threatening liabilities. Samples were made from a ternary mixture of ground Oyster shell as abrasive, Bakelite powder as Binder and two plies of Glass fiber as reinforcement through hot pressing. Formulation with 60% OSA offered 79 Shore D hardness and wear rate of 0.0002g/min which were superior to a commercial product. Microscopic evaluations revealed an even distribution of pores and the OSA grains in the Bakelite matrix with DSC results demonstrating a thermal conductivity of 0.1232W/m/K. TGA results showed a two-step thermal degradation. First was loss of moisture at 1.432mg by weight at 211.85 ^{o}C with second step being thermal decomposition of 6.352mg showing a thermal stability of 53.16% at 418.70 ^{o}C.

Keywords: Oyster; abrasive; conductivity; hardness; wear

1. Introduction

Scrap development at the machining stage of manufacturing process is highly prohibited considering the resources and investment committed to the product from the raw materials stage [1].Grinding is the last manufacturing process prior to coating, glazing or painting and must be carried out with utmost proficiency as it represents a quarter of the entire machining cost [2].It is a finishing and subtractive manufacturing operation for shaping, sharpening and smoothening surfaces using frictional interaction between the workpiece and grinding tool. It involves shear deformation of workpiece particles in a way that they are either compressed onto the grinding surface to obtain dimensional uniformity or removed to secure uniform shape, even-out rough surfaces and to maintain a smooth surface. The kinetic energy due to the frictional interaction generates heat that is distributed between the two participating materials (Grinding wheel and workpiece) from the point of interaction to subsurface regions with some part of the energy dissipated to chips and coolants[3]. As a thermomechanical interaction, this heat is beneficial because it causes an annealing heat process that softens the contact surface making grinding easier than the onset. However, excessive heating leads to detrimental results such as microstructural transformations, burning, deformation, quench heat treatment due to coolant heat transfer etc that lead to fracture, surface restructuring etc. Overheated grinding surfaces can cause excessive tool wear, residual stresses, hardened surface relative to adjacent regions of the mating surface that result to crack initiation and propagation. It can also heat up the produced chips which trigger spark jets that can cause fire hazard during grinding operations. This extreme hotness can also cause burning of the grinding wheel binder which weakens adjacent abrasive grains to be knocked out of position and consequently affects grinding efficiency. This heat generation can be regulated via controlled feed rate, grinding speed and use of appropriate coolants that can sweep the heat away. On cooling, this elevated temperature if rapidly evacuated by a coolant causes a quench heat treatment and if cooled by the underlying air in dry-grinding operations causes a normalized microstructure. In either situation, microstructural phase transformations occur that may not be beneficial to the material's properties. This heat can also cause grinding burn of the workpiece surface leading to both aesthetic deterioration and mechanical plastic deformation.

During grinding, materials are removed from the mating surfaces and must be evacuated otherwise their entrapment within the mating surface or within the void cavities can cause severe reduction of grinding efficiency. This happens because the composite of chips and abraded parts of the grinding tool accumulates the heat generated which causes localized heating of the grinding tool without contributing to the grinding process. This heat enhances the ease of blunting the newly exposed abrasives. Also, the rate of heat generation and subsequent evacuation by coolants causes rapid thermal expansion and contraction consequently leading to residual stresses in the ground component [4]. Furthermore, the rapid thermally induced decomposition of the grinding tool made from carbonaceous materials leads to breakdown of calcium carbonate to calcium oxide with the emission of carbon dioxide to be inhaled by the grinding operator. Also, the grinding wheel grains are expected to be thermally stable in the presence of the generated heat otherwise they will decompose and get blunt. This blunting phenomenon reduces the grinding efficiency of the tool. It can be seen that most grinding process damages are thermally activated [5]. Hence, the thermal stability of the grinding tool becomes very important both in health and structural concerns, thus, requires appropriate empirical investigation as considered in this study. The Thermogravimetric analysis (TGA) and Differential Scanning Calorimetry (DSC) are established methods of determining the thermal behaviour of materials as they supply details of its irreversible degradation and oxidation reactions based on Time or Temperature dependent weight losses and heat flow [6] and were adopted in this study.

Significant attention has been focused on the workpiece's heat flux as well as the highest temperature rise which must be constrained within the burn threshold for an optimized grinding process [7], however, this accounts for 10% of the generated heat, the produced chip bears 80% while the less studied grinding tool bears the rest [8-9]. [5] studied the energy partition which is the part of the grinding energy at the grinding surface conveyed as heat to the workpiece which depends on the grinding conditions, type of grinding operation, the nature of the workpiece and the grinding tool. Primarily, since the grinding tool is made of the abrasive and binder and the binder is not thermomechanically accountable, then, the responsibility of thermal stability of the workpiece relies on the abrasive grains which is expected to conduct the heat away.Then the grinding tool grains need to be thermally stable to sustain the grinding operation effectively. However, since the tool consists of the binder and abrasive grains [10] and the binder is thermally weaker, it is expected to degrade before the abrasive particles hence requires investigation too. In fact, the tool's temperature is a determinant factor in tool life since the principal tool properties deteriorate at elevated tool temperatures. There is need for heat dispersion away from the grinding tool to protect binder thermal decomposition that will affect tool life. Bakelite as a stable resin was chosen in this study because according to [10] resinous bonds are the most popular matrix due to their self-sharpening potentials next to vitrified bond when used in grinding wheels. Similarly, fiber glass is a globally recognized reinforcement fiber with high temperature resistance. As a ternary mixture, the only unfamiliar component to this study was the Oyster shell grains as the abrasive for the grinding wheel production.

2. Materials and Methods

Resin-bonded grinding wheels were compounded via hot pressing with the resin-abrasive-reinforcement mixture filled in a mold. The mold was patterned with the negative of the desired grinding wheel shape and size [11]. This operation occurred under compression at predetermined temperature and pressure of 300 ^{o}C and 40 MPa respectively.

2.1 Production of grinding wheel

The novel composite produced to function as a grinding wheel was made from Oyster shell as an abrasive, Bakelite powder as the binder and glass fiber as the reinforcement material.

The carbon fiber was used as received with no further material modification except that it was cut into Ɵ42 mm suitable for the cup mold. Likewise, the Bakelite was used without further material preparation except that it was sieved into 350 μm to avoid agglomeration during material mixing. However, the Oyster shells were procured from the seafood section of Choba market in Port Harcourt. It was oven-dried at 50 ^{o}C for 2hours to increase its friability before being crushed in a ball mill. The coarse-grained powder was further ground into fine powder prior to sieving into 500 μm particles and stored in zip-lock bags to avoid moisture.

The ternary mixture of Oyster shell, Bakelite and fiber glass was filled in the mold with Bakelite and Oyster shell in a ratio of 3:2 alongside two layers of fiber. The mold and lid surfaces were rubbed with Talc as a release agent prior to filling the mold with the ternary mixture. A thermocouple was fixed into the mold to measure the temperature before the entire hot press assembly was connected to electric power supply at a hydraulic pressure set to 400MPa. While both pressure and temperature build up, as an automated system, the hot press triggers off when the pressure and temperature were attained. The composite formed from the abrasive, binder and fiber was easily ejected from the mold assembly through the help of the release agent (Talc) while the grinding wheel was finally formed under controlled cooling in still air.

To test for the effect of abrasive content, the process was repeated by changing the Oyster shell content from 40 to 80%.In this study, six grinding wheels were produced designated as S_1, S_2, S_3, S_4, S_5 and S_6 based on 30, 40, 50, 60, 70 and 80% Oyster shell contents respectively. To make comparative analysis of their properties, sample (S_7) was added being a commercial grinding wheel bought from the market. From the

Grinding wheels produced and the commercial product, samples were cut to conduct physical and thermal analysis.

2.2 Physical analysis

2.2.1 Hardness Test

The Durometer hardness number of a grinding wheel is one of the most important physical properties of polymer bonded composites as it records the degree of abrasion or rate of material loss as a measure of indentation on the surface with respect to the polymer as the softer component. As a Bakelite bonded grinding wheel, 6.4 mm thick samples were machined from the grinding wheels for the Force-Time based Durometer test to predict tool longevity in line with ASTM D2240-15 [12] standard. The sample was held on a jig mounted on the specimen support table of the testing machine while observing the degree of indentation depth using a spring-loaded indenter made of hardened steel. As a static test method, all sources of vibration were eliminated while the PosiTector SHD D 30° cone-tipped indenter was pressed down firmly on the sample surface. In line with ISO 48-4 standard, the dial readings recorded after 15 seconds of applying a 5kg load on a 44.5 N and 49.0 N spring and contact forces respectively. This was done in triplicate positions on the wheel surface separated 6 mm center distance apart and at 10 mm from the sample edges with the mean hardness values of each sample presented in section 3.1.

2.2.2 Wear Test

The pin-on-disc method used in this study measured the two-body sliding wear behavior on rotation mode using a 10N loaded dry-run on a high strength steel surface in accordance with [13]. A 6.4mm rectangular specimen was prepared with very flat tip recognized as the pin while the steel plate of the machine was mirror-surface cleaned recognized as the disc for the pin-on-disc operation. The pin sample from the composite was fixed tightly in the chuck of the machine pin arm with a 10 N force attached on it before the pin assembly was gently dropped on the perpendicular disc surface. As the motor was switched on, the mating surfaces were in good contact with the composite sample being stationary while the disc moved to trace a circular path. Initial and final weights of the samples were recorded after 600 seconds run with weight loss values presented in table 1.

Table 1: Ten Minutes Wear Rate of Produced Grinding Wheels and The Commercial Sample.

Sample ID	Initial Weight, g	Final Weight, mg	Weight loss, g	Wear rate, g/min
S_1	1.1539	1.1114	0.0425	0.00425
S_2	0.6221	0.6122	0.0099	0.00099
S_3	0.7913	0.7809	0.0104	0.00104
S_4	2.3784	2.3762	0.0022	0.00022
S_5	4.9500	4.9388	0.0112	0.00112
S_6	2.8379	2.7992	0.0387	0.00387
S_7	0.6842	0.6805	0.0037	0.00037

2.3 Thermal analysis

2.3.1 Thermal conductivity

The thermal conductivity of the composite was carried out using Mettler ToledoDSC822 operated at a constant heating rate of 10 ^oC/min under Nitrogen as the purge gas with the reference crucible being empty. By measuring the heat flow per temperature as the sample melts, the DSC scan was run until 500 ^oC.

2.3.2 Thermal stability

The thermal behavior of the grinding wheel composite was analyzed using the Shimadzu DTG-60H model (TA Instruments, USA) in line with the procedure in [14]. A simultaneous thermal analyzer (Differential Thermal Analysis-Thermogravimetric Analysis, DTA/TGA). This thermal analysis was conducted by placing 11.9470mg of the sample in a Platinum cup which was heated in a furnace alongside a reference crucible from 22.93 ^oCup to 1200^oC. The heating ramp was set to 10 °C/min while the furnace atmosphere was Nitrogen gas flowing at 50 ml/h. Thermal profiles for property evaluations were obtained after a one cycle run was cooled under instrument atmospheric conditions with results presented in subsequent sections of this study.

2.4 Microscopic Evaluation

The microscopic assessment of the grinding wheel samples produced were viewed using Keyence VH-Z450/VH-6300 Digital Microscope with VH-Z450 High-Range Zoom Lens at 500X magnification following the procedure in [14]. Prior to microscopic investigation, the sample preparation carried out were mild surface polishing using moist emery paper to expose microscopic feature free from dirt and dust. The residue from the polished surface were got rid of through running water rinsing followed by sun-drying for 2 hours.

3. Results and Discussion

3.1 Shore D Hardness Number

Results of the Durometer hardness test conducted in section 2.2.1 are presented in fig. 3.1.

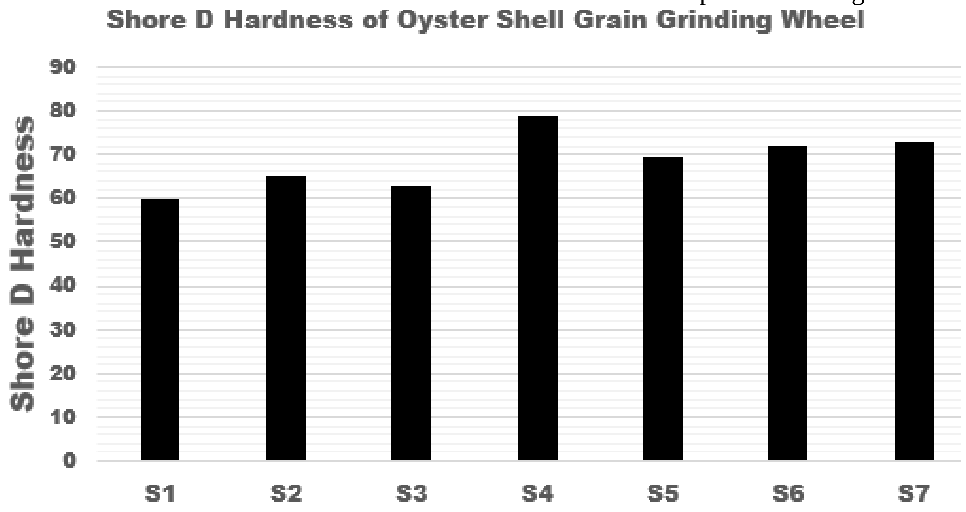

Fig. 3.1: Shore D Hardness of Oyster Shell Grain Grinding Wheel

From fig. 3.1, it can be noticed that sample S_4 had the highest Shore D hardness number of 79 Shore D at standard dwell time (SDT). This is the sample containing 60 % Oyster shell in the composite. Remarkably, this result was higher than the hardness of the commercial product with 73 Shore D at SDT. This 7.59% gain in Shore D hardness by using Oyster shell grains as abrasives in grinding wheel production is highly recommendable for market driven potentials in addition to its environmental and sustainable benefits.

3.2 Wear rate of Produced Grinding Wheels

Data obtained from the pin-on-disc operation were used to display the results shown in fig. 3.2 which demonstrated both the weight loss and the wear rate of the samples tested.

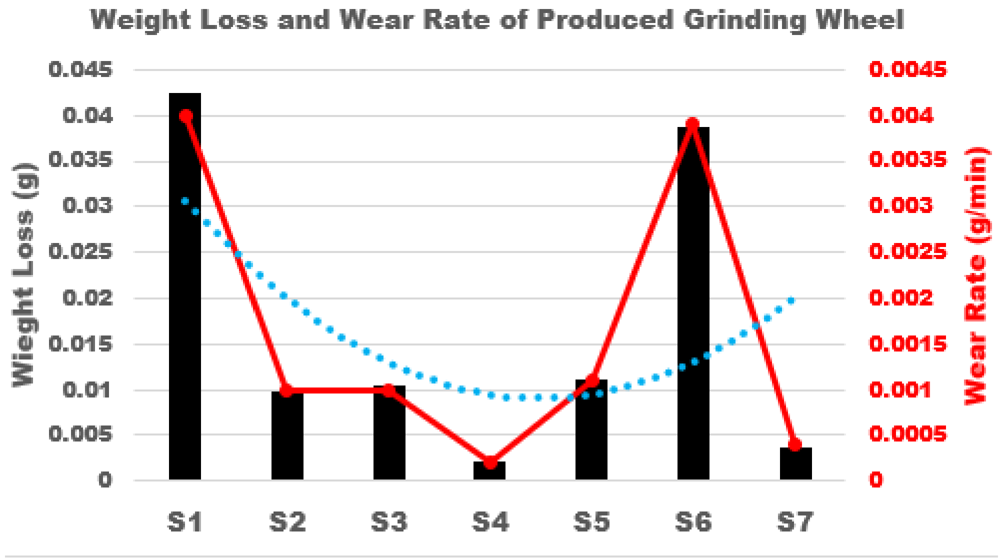

Fig. 3.2: Weight Loss and Wear Rate of Produced Grinding Wheel

From fig. 3.2, it can be seen that sample S4 had the least weight loss of 0.002g after 10 minutes leading to a wear rate of 0.0002g/min. Interestingly, this result was superior to the product obtained from the market which had a wear rate of 0.0004g/min. from this record, the best recipe in this study made a 50% savings in wear rate of the grinding wheel. Also, from the graph, it can be seen that the weight loss and wear rate followed the same trend showing that both measures can be used to explain the abrasive properties of the grinding wheel. Furthermore, fig. 3.2 reveals from the trendline (blue line) that the wear rate decreased continuously from S1 until sample S4 before it started to increase again. This shows that increasing the abrasive grain content of the composite reduces the rate of wear but to an extent where it begins to wear rapidly as the grain composition increase. It can be attributed to the fact that beyond 60% of the abrasive composition, the binding force of the Bakelite begins to fail and more of the abrasive grains are lost due to reduced binding force instead of frictional force of the grinding operation. Hence, the best recipe for formulating a grinding wheel using Oyster shell particles is 60% of grain embedded in 40% of Bakelite powder in a 2-ply fiber glass reinforcement.

3.3 Thermal conductivity

Results from the thermal conductivity test in section 2.31 is presented in fig. 3.3. This was deduced from software calculations at the onset of melting of the composite.

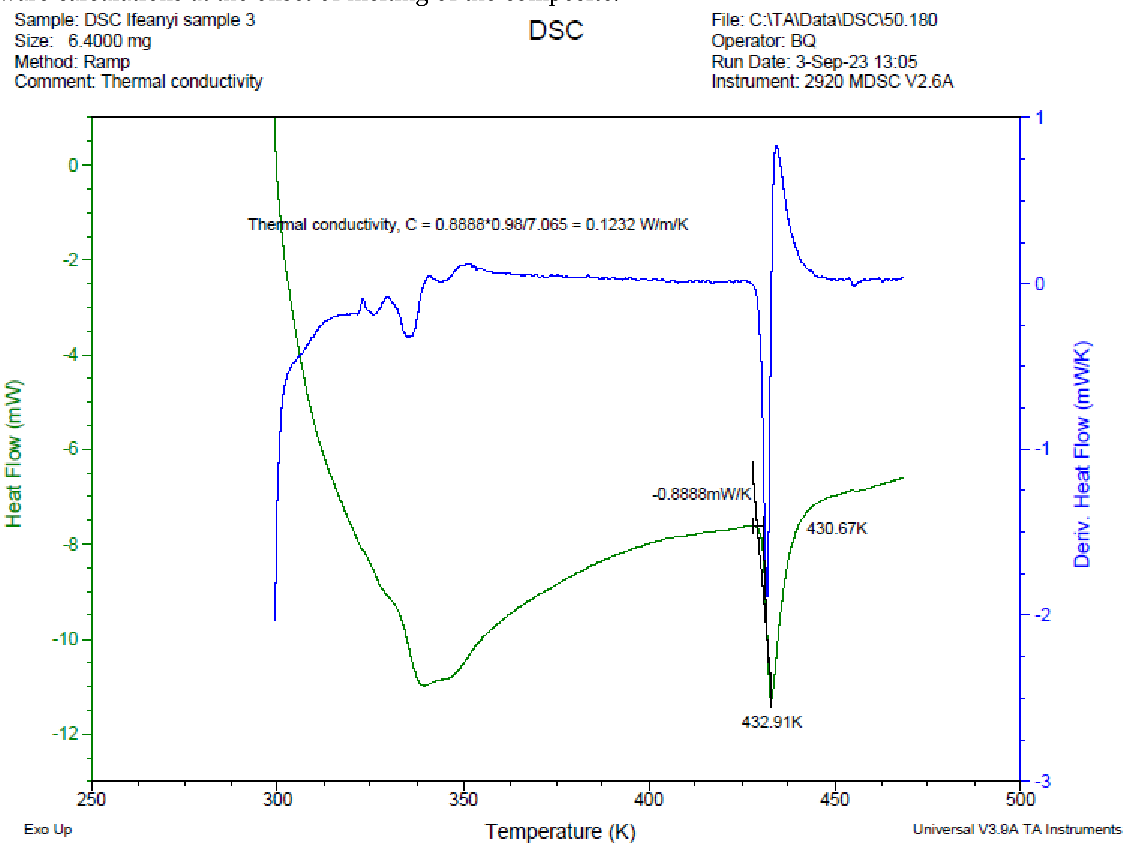

Fig. 3.3: Thermal Conductivity of the Produced Grinding Wheel

From the derivative curve, it can be seen that as the curve approaches the melting peak it became linear but decreased exponentially after the melting point, with the aid of the software, the slope was calculated and its calculations with the thermal resistance were used to deduce the thermal conductivity of the grinding wheel sample. From the result, it can be seen that the thermal conductivity was o.1232W/m/K. This thermal conductivity was less than the result (0.71 W/mK) obtained from obtained in [15] from their best recipe of Graphite, SiC and Epoxy Resin composite in a thermally insulating purpose. Also, this result can be seen to be very low showing that the wheel will be very insulating to the frictionally generated heat during grinding. Also, this insulative behavior protects it from thermally-induced wear and may be the reason why the sample maintained a lesser wear rate than the commercial product procured from the market. This was conducted on the S4 sample which demonstrated excellent physical properties.

3.4 Thermal behavior of Produced Grinding Wheels

The thermogram in fig.3.4 shows the TG/DTG curves for the thermal decomposition of the produce grinding wheel.

As can be seen from the thermogram, about 17.323% of the weight loss occurring around 211.11oC can be attributed to loss of moisture content of the composite. This first fall of the TG curve started immediately from the onset temperature of 23°C and continued rapidly until it plateaued before 211.03°C.The second peak in the first derivative thermogravimetry DTG corresponds with a remarkable drop in weight with onset from 211.03°C and proceeded until 411.11°C. This thermal degradation can be attributed to bond braking and disentangling of the Bakelite polymeric bonds leaving a residue of 34.83%. It is evident that the wheel demonstrated a two-step degradation between 22.93°C to 500°C. These thermal peaks demonstrate typical exothermic processes which were accompanied with heat loss during the weight loss. Hence, with this thermogram, it was easy to study the decomposition of the produced grinding wheels as a simulation of the frictional generated heat in real operation.

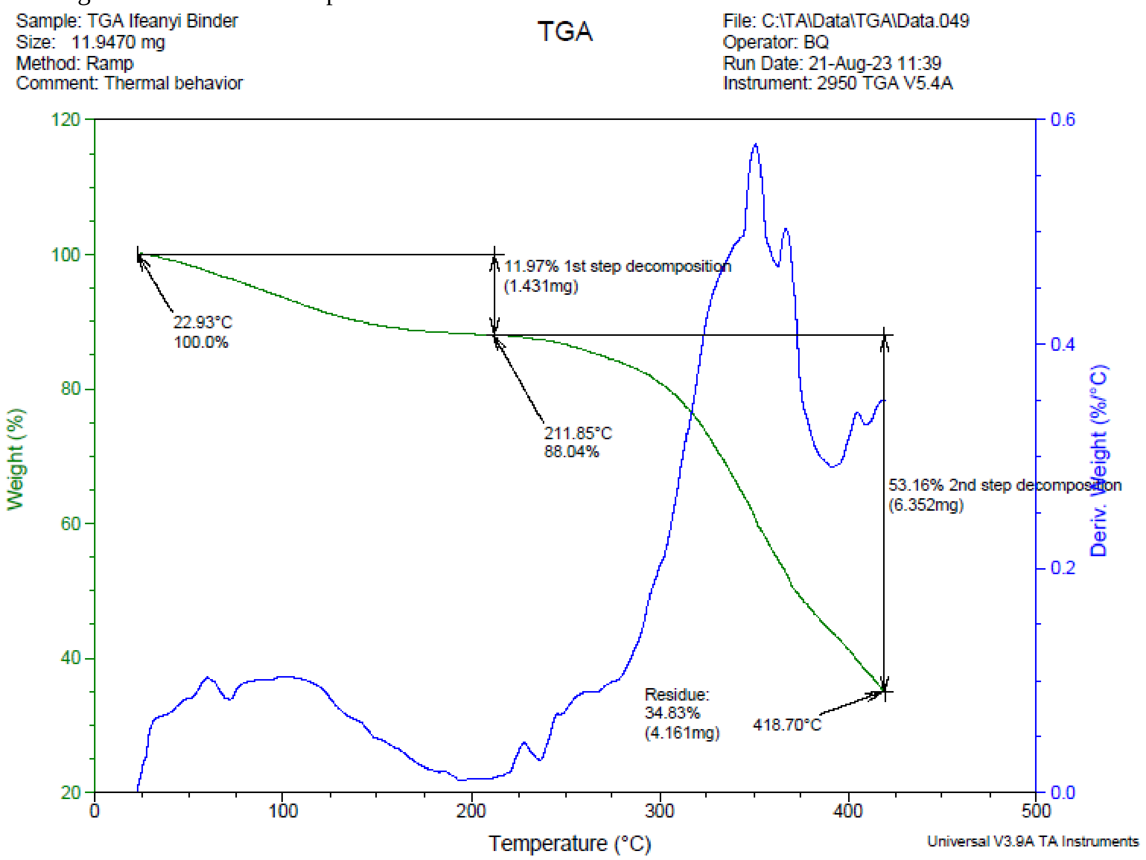

Fig. 3.4: TGA curve showing the thermal behaviour of the Produced Grinding Wheel

3.5 Microscopic Evaluation

Results from the microscopic examination of the Oyster-grained abrasive grinding wheel are presented in fig. 3.5. It can be seen from fig. 3.5 that there was an even distribution of abrasive particles (white) in the Bakelite matrix (Green). Presence of pores were also identified (Black). As a ternary mixture of Oyster shell abrasive grains labelled (A), Bakelite Binder (B) and the Glass fiber (F) reinforcement, the fiber glass component was revealed in a lateral section shown in fig. 3.5b with presence of interparticle pores labelled (P) in fig. 3.5a.

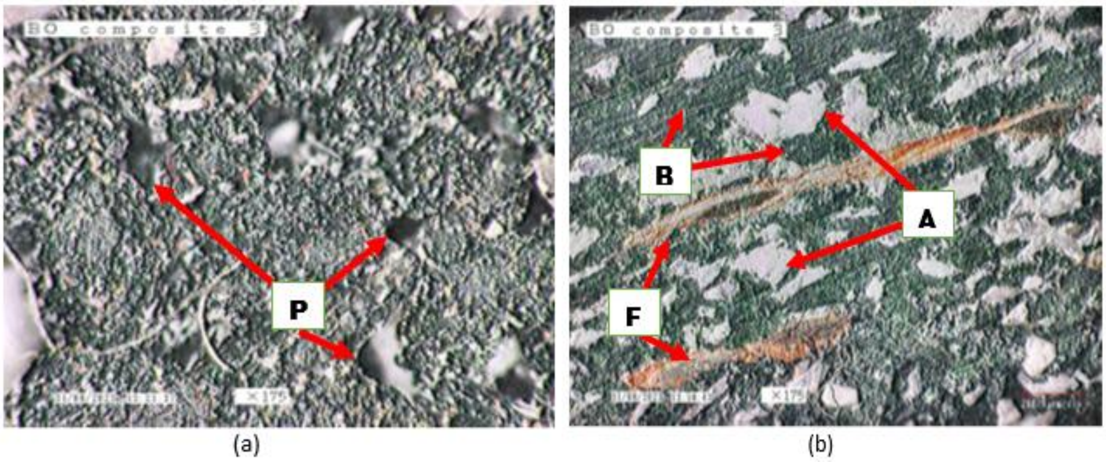

Fig. 3.5: Micrographs of the Produced Grinding Wheel (a) Pores (b) 2 plies of fiber glass

4. Conclusion and Recommendation

This study investigated the potentials of Oyster Shells as potential abrasives for formulating industrial grinding wheel production recipes. The ternary mixture of Oyster shell particles as abrasive grains, Bakelite powder as Binder and two plies of Glass fiber as reinforcement. From different recipes, the formulation with 60% oyster shell offered the best results of 79 Shore D at SDT and wear rate of 0.0002g/min which were relatively superior to a commercial product. Microscopic evaluations revealed presence of pores and even distribution of the oyster shell grains in the Bakelite matrix. Results from Thermogravimetric Analysis showed that the grinding wheel went through two step thermal degradation at 211.85^{o}C and 418.70^{o}C respectively. The first degradation being loss of moisture occurred with 1.432mg loss of weight while the second lost 6.352mg from the 11.9470mg of the initial starting material. This showed that the grinding wheel's thermal stability was 53.16% degradation at 418.70^{o}C. Also, Differential Scanning Calorimetry thermogram revealed a thermal conductivity of 0.1232W/m/K. These thermal and physical properties show the potentials of Oyster Shell particles as abrasive grains for producing industrial grinding wheels in 2-ply carbon fiber reinforcement and Bakelite matrix. It is hereby recommended for industrial validation and application as environmentally sustainable and waste recovery source of abrasive grains that suits any market-driven technology.

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