APPLICATIONS OF ADDITIVE MANUFACTURING IN THE PRODUCTION OF AUTOMOBILE PARTS FROM POLYMERS AND NATURAL FIBER REINFORCED POLYMER COMPOSITES

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In Partial Fulfilment of the Requirement for the Degree of Master of Science
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By

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Abuja-Nigeria

April, 2021

CERTIFICATION

This is to certify that the thesis titled APPLICATIONS OF ADDITIVE MANUFACTURING IN THE PRODUCTION OF AUTOMOBILE PARTS FROM POLYMERS AND NATURAL FIBER REINFORCED POLYMER COMPOSITES submitted to the School of Postgraduate studies, African University of Science and Technology (AUST), Abuja-Nigeria for the award of the Master’s degree is a record of original research carried out by KUMACHANG CYRIL CHU FUBIN (40743) in the Department of Materials Science and Engineering.

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A THESIS APPROVED BY THE MATERIALS SCIENCE AND ENGINEERING DEPARTMENT

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ABSTRACT

The rate of CO_2 emissions from manufacturing industries and some manufactured products in service or at the end-of-life use is really troubling and needs attention. The CO_2 contribution from the automotive or transportation industry is far higher than those of other sectors. Often times, the transportation industry uses materials such as steel and iron which are not only less ecofriendly but heavy as well. This increases the weight of vehicles thereby increasing fuel consumption which by default results to an increase in CO_2 emissions. Also, some conventional methods of manufacturing often used in the automotive industry have a high energy requirement with associated CO_2 emissions. That is why this research generally focuses on the evaluation of additive manufacturing (AM) as a novel method of manufacturing with a lower energy requirement. Specifically, this work focuses on: The preparation of computer aided design (CAD) model data of some automobile parts for 3D printing using PLA (Poly Lactic Acid). The investigation of the microstructures and mechanical properties of the 3D printed materials using the scanning electron microscope (SEM) and the Instron Universal Testing Machine respectively. We were able to show in this work that the application of AM in the automotive industry is possible and is capable of producing lightweight structures with enhanced mechanical properties. A theoretical assessment of the use of Natural Fiber-reinforced Polymers (NFRPC) in the production of 3D printing filaments for AM was made and found to have the capability of contributing in mitigating the effects of climate change due to CO_2 emissions.

KEYWORDS: Additive manufacturing, automotive parts, composites, natural fiber reinforced polymer, 3D printing, poly lactic acid, computer aided design, mechanical properties.

DEDICATION

I Dedicate this work to my beloved uncle, Prof. Benjamin Akih-Kumgeh, Associate Professor of Mechanical and Aerospace Engineering, Syracuse University. His support and encouragement towards my academics have been tremendous.

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I thank the Almighty God for giving me the opportunities to carry out this research in a domain I really like and for seeing me through all the challenges I encountered in the course of the work. I also thank the African University of Science & Technology (AUST) as well as its funding organizations for giving me admission and a scholarship to acquire this world-class education that has greatly impacted my life and career. I pray God continue to bless **Prof. Azikiwe Peter Onwualu, Prof. Wole Soboyejo** and **ALL** my AUST lecturers for their time, knowledge and contributions towards the realization of this work. This list of acknowledgements will not be complete without mentioning my beloved family for their encouragement and support towards my life, academics and career. I equally want to thank Dr. Anye Vitalis, Dr. Bello, Dr. Tido, Mr. Tonny and Mr. Greg for the support they accorded to me at the ADB laboratory while carrying out this work. And to all my beloved classmates and friends, you guys have really been wonderful in this journey. I thank God for letting our paths to cross. Last but not the least, I appreciate the support I received form the Cameroonian community I met at AUST especially Mrs Odette Anye, Daizy-clay, Ronald, Linda and Greg.

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CHAPTER ONE

1.0. INTRODUCTION

1.1. Background to the Problem

The protection and preservation of the natural environment has become a major preoccupation. This has pushed most manufacturing industries whose products have associated Carbon dioxide emissions to start exploring alternative environmentally friendly materials for their manufacturing.

The transportation of people and goods from one place to another is an important aspect of life. Most transportation vehicles are powered by hydrocarbon fuel driven combustion engines which emits toxic gases such as Nitrogen oxides (NO_x¿ and Carbon dioxide (CO_2¿ as well as other substances that are detrimental to the environment and our health. Carbon dioxide (CO_2¿ is the main source of global warming and climate change [1,2]. It is a greenhouse gas that absorbs and emits radiations in the thermal infrared range thereby causing greenhouse effect which increases the temperature on the earth surface. In order to avoid a collapse of major climate pattern and minimize the risk for an irreversible change of global warming, it is recommended that the concentration of the Carbon dioxide (CO_2¿ in the atmosphere should not exceed 350 parts per million (ppm) [3]. Currently, the concentration stands at 387ppm which is already beyond the lower limit but in the zone of uncertainty with an increasing risk. If we must continue to operate safely on earth, the Carbon dioxide (CO_2¿ emissions from transport and other sectors must be reduced [4].

Carbon dioxide (CO_2¿ emissions from vehicles depend on two factors; the Powertrain efficiency and driving resistance [1]. The driving resistance parameters are aerodynamic drag, rolling resistance and acceleration [5]. The rolling resistance and acceleration depends on the mass of the vehicle [5]. An improvement in the powertrain efficiency results in a decrease in fuel consumption; however, it is not permissible to improve the powertrain efficiency due to physical laws. In view of a solution to the Carbon dioxide (

CO_2¿ emission problem in the automotive industry, there is a technological shift towards electrified powertrains [1]. Although the Carbon dioxide (CO_2¿ emission from Electric vehicles is reduced during use, there are still possibilities of Carbon dioxide (CO_2¿ emission from the production of the electricity used to power the vehicles such as in the case of electricity production via the burning of fossil fuel. Also, the materials often used in the production of batteries and other electric components for electric vehicles have associated negative environmental impact. This seem to suggest that electric vehicles might just be a way of transferring the Carbon dioxide (CO_2¿ emission from one source or life cycle phase to another thereby making both electric and conventional Internal Combustion Engine powertrain of almost the same environmental impact.

A reduction in weight will lead to an increase in energy efficiency of all vehicles irrespective of the powertrain. Weight reduction of aircrafts has been successful through the use of polymer composites especially carbon fiber reinforced polymer composites (CFRP) which poses excellent stiffness and strength to weight ratio [6]. This design approach has equally been used in high performance sports cars as well as some standard cars in order to improve performance and energy efficiency [1]. A major challenge with polymer composites is the energy requirement for the production of the raw materials especially carbon fibers and the limited recycling opportunities of the composite materials [7].

In recent years, researchers have been exploring other sustainable and environmentally friendly materials for the automotive industry. Natural fibers reinforced polymer composites are promising to be better alternatives owing to their lightweight, environmental friendliness and attractive mechanical properties. Other researchers are exploring the versatility of additive manufacturing as a method of production of automobile parts owing to its less energy requirement and recyclability of 3D printed materials.

1.2. Statement of the Problem

As a statement to the problem and a summary of what we have been discussing so far, the rate of CO2 emissions from manufacturing industries and some manufactured products in service or at the end-of-life use is really troubling and needs attention. The CO2 contribution from the automotive or transportation industry is far higher than those of other sectors. Often times, the transportation industry uses materials such as steel and iron which are not only less ecofriendly but heavy as well. This increases the weight of vehicles thereby increasing fuel consumption which by default results to an increase in CO2 emissions. Likewise, some conventional methods of manufacturing often used in the automotive industry have a high energy requirement with associated CO2 emissions.

This research focuses on the characterization of 3D printed materials for automotive applications using polymers and natural fibers reinforced polymer composites with the hope of weight reduction and increased energy efficiency.

1.3. Aim and Objectives

The general aim of this research is to investigate the possibility of applying additive manufacturing in the automotive industry to produce lightweight automobile components with enhanced mechanical properties using polymers and natural fiber reinforced polymer composites.

The specific Objectives are as follows:

- Prepare Computer Aided Design (CAD) files of some automobile parts and 3D print with Poly Lactic Acid (PLA) and Natural Fiber Reinforced Polymer Composite filaments.
- Investigate the microstructures and mechanical properties of the 3D printed materials.

1.4. Scope/Justification

There are different methods of additive manufacturing (AM). This work will make use of the Fused Deposition Modeling (FDM) also known as the Fused Filament Fabrication (FFF) technique since we will be using the Lulzbot Taz 6 3D printer at AUST.

Similarly, though we are surrounded by a good number of polymers or plastics (Commodity and engineering plastics), this work will be focused on the use of Poly Lactic Acid (PLA) as a printing filament and Natural fiber reinforced recycled Polyethylene terephthalate (NFRrPET). The choice for recycled Polyethylene Terephthalate (rPET) polymer is influenced by the growing concerns on the nuisance these used plastics are to our environment. Also, it has been proven that recycled engineering plastics such as rPET still maintain good mechanical properties suitable for advanced engineering applications than recycled commodity plastics.

Meanwhile of the many natural fibers available with good thermomechanical properties for automotive applications, this work will be based on the banana fiber due to its high cellulose content which influences its thermomechanical properties positively and the relative abundance of banana in Sub-Saharan Africa.

1.5. Thesis Organization

This Thesis is arranged as shown in Fig 1:

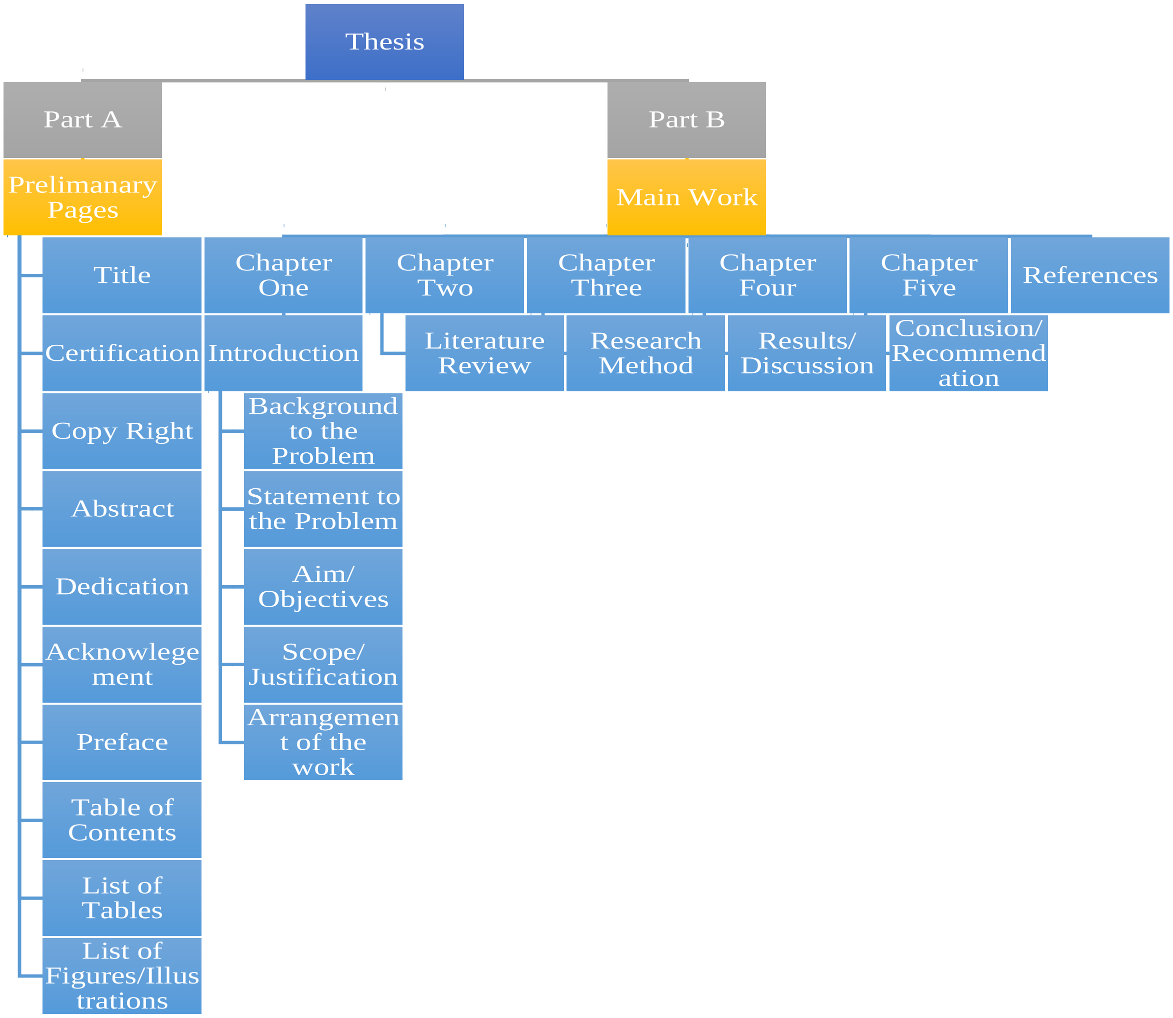


Figure 1: Thesis Organization

CHAPTER TWO

2.0. LITERATURE REVIEW

2.1. Additive Manufacturing

Additive manufacturing (AM) also commonly referred to as 3D printing is the layer-by-layer construction of a three-dimensional object from a computer aided design (CAD) model or digital 3D model [8]. According to the American Society for Testing and Materials (ASTM) International Committee F42 on AM technologies, AM is the process of joining materials to make objects from three-dimensional (3D) model data, usually layer by layer, as opposed to subtractive manufacturing methodologies [9]. Subtractive manufacturing is a traditional method of manufacturing in which parts are made, stamped or molded from larger pieces of materials [10]. Some people refer to AM as the “third industrial revolution” due to its potential to change the manufacturing industry. The input in the AM process is a 3D model data drafted with a computer designing software [11]. Today, AM is promising to be a technology with large scale applications in the automotive, aerospace and biomedical industries [12].

According to ISO/ASTM 52900, the AM technology is classified into single step and multistep processes. Depending on the material used in the AM process, we can have three main types of AM process namely Liquid-based, Solid-based and powder-based AM processes. The stereo lithography (SL), fused deposition modelling (FDM) and polyjet are liquid-based AM techniques. While powdered bed and inkjet head AM, laminated engineered net shaping, pro-metal, selective laser sintering (SLS) and electron beam melting are powdered-based techniques of AM [13].

Of all the techniques of AM, fused deposition modelling (FDM) is the best and the most commonly used in many settings due to its ability to support manufacturing with a range of materials including composites [14]. The FDM process of AM was developed in the 1980s and commercialized in the early 1990s by the Stratasys Inc., USA. The FDM technique is reliable, cost-effective in producing 3D materials with good resolution, dimensionally stable (Harun et al. 2009), simple in its fabrication process and can fabricate parts with complicated geometries. But the FDM technique have as one of its major drawbacks the presence of voids between deposition lines in materials printed with composites [15]. However, these voids have a major advantage in applications with acoustical requirements since they are capable of absorbing sound waves effectively. To ensure that products are made with enhanced properties, filaments for AM process needs to be durable and resistant [16]. Several materials such as pure polymers, polymer matrix composites, polymer ceramic composites, nanocomposites and fiber-reinforced composites have found applications in the AM process [12]. Lately, researchers are exploring the possibilities of using natural fiber-reinforced composites (NFRC) filaments for AM process due to their low cost, biodegradability and eco-friendliness [17].

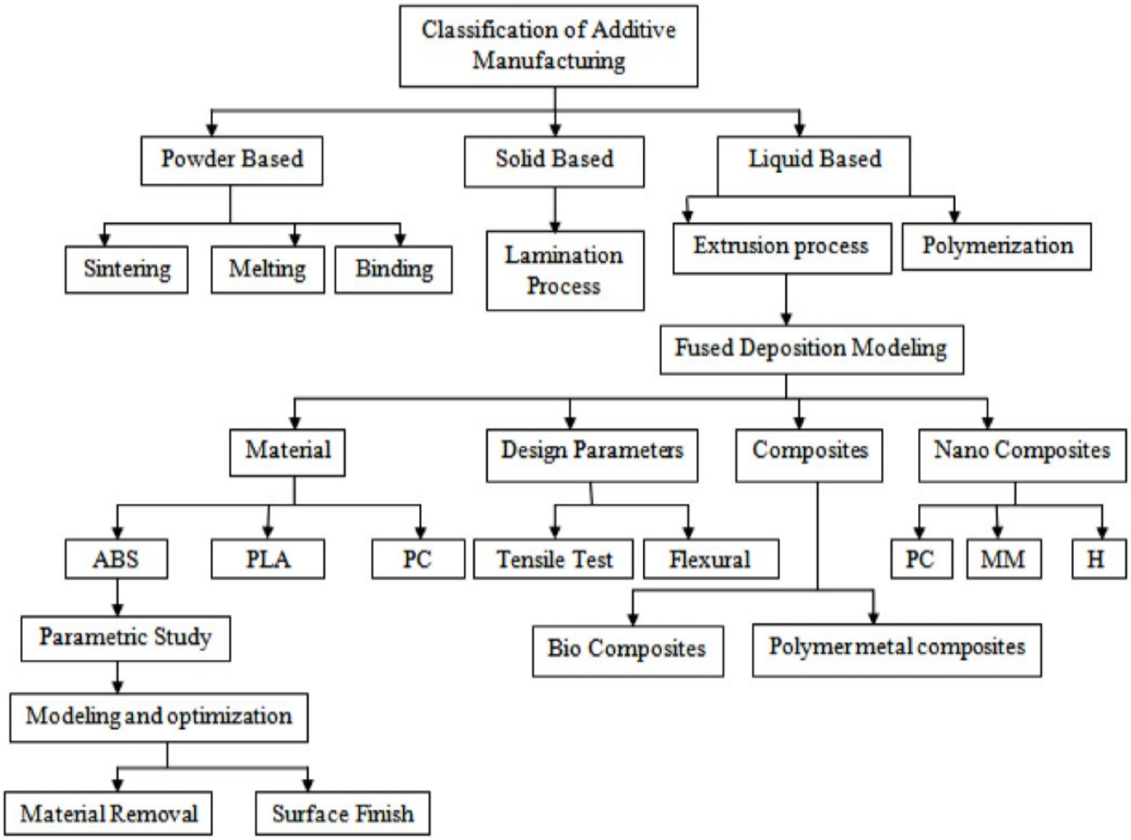


Figure 2: Classification of Additive Manufacturing [18]

2.2. Polymers

Polymers can easily be thought of as useful chemicals made up of repeating building blocks or units called monomers. The process by which monomers combine to form polymers is commonly referred to as polymerization. The classification of polymers can be done based on their occurrence, response to thermal changes, physical properties, mode of formation and online structures [19]. The figure below shows a summary of this polymer classification.

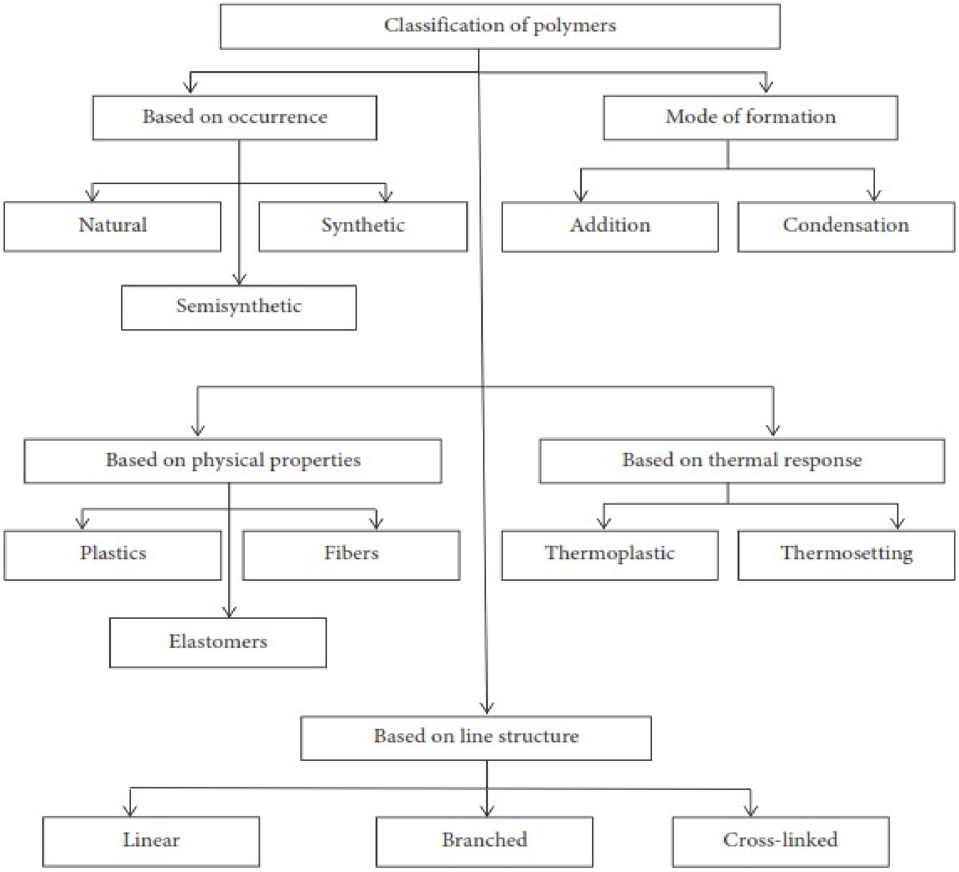


Figure 3: Classification of Polymers [8]

There are many polymers such as polyethylene (PE), polypropylene (PP), polystyrene, polycarbonate and polyester that we can use as polymers or matrices in polymer composites for additive manufacturing. However, due to the high working temperature (300℃) of the fused deposition modeling (FDM) technique of additive manufacturing, only thermoplastics and a few other polymers find their way into the additive manufacturing process [12]. Thermoplastics are polymers that can repeatedly be melted and recast. When heated above the threshold temperature, they become molten and upon cooling, they harden [20]. Examples of thermoplastics include Acrylonitrile Buta-styrene (ABS), polyethylene, polypropylene, polystyrene, polyvinylchloride (PVC), Nylon, Acrylic and Teflon. Also, thermoplastic polymers are preferred for 3D printing because they do not detach during the entire additive manufacturing process unlike other polymer counterparts [8]. Polymers used for additive manufacturing are either obtained from recycled plastics or from bioplastics. Examples of polymers obtained from recycled plastics include poly(lactic acid) and acrylonitrile butadiene styrene (ABS). Meanwhile examples of polymers obtained from bioplastics include PLA and polydroxyalkonates (PHA) [8]. The production cost of PLA is lower [8] while the production cost of PHA is higher [21].

Experiments on extrusion additive manufacturing with carbon fiber-reinforced PLA filaments conducted by Ivey et al showed that PLA holds good for the extrusion additive manufacturing process for the fiber content of 15%. Other research by Rodriquez et al using specimens produced from ABS and PLA by FDM additive manufacturing showed that specimens made using PLA exhibits good rigidity, increased tensile strength and strong bonds between layers of PLA. They concluded that PLA is most suitable for the additive manufacturing process [22].

PLA is one of the thermoplastic aliphatic polyesters synthesized from raw materials like rice, corn and sugar beets. As compared to other biodegradable polymer materials, PLA is nontoxic and has a good renewability and compatibility [23]. As a polymer matrix with natural fibers as reinforcement, PLA has proven to be most economical and efficient system that can be widely used for many applications [24]. PLA requires less energy for its production and is one of the best ecofriendly polymers with a higher degradation rate when filled in lands. Bioplastics causes a negligible global warming effect as compared to conventional plastics [25]. The carbon footprint of PLA as a material is less when compared with other polymer counterparts except during its processing that the carbon emission is comparatively higher than other polymers [8]. Used PLA filaments can be recycled and reused with fairly similar mechanical properties [26].

However, some limitations, mainly the innate brittleness and low impact strength have been registered with the usage of pure polymers like PLA [27]. We can overcome these limitations by reinforcing polymers with fibers to form composites that can be used for many applications due their strengths, cost reduction and lighter weights [8].

2.3. Fibers and their Classification

Generally, fibers are hair-like substances with a high degree of fineness, outstanding flexibility, reasonable strength and ability to hold to one another when placed side by side (minimum level of length and cohesiveness) [28]. Fibers with a length of at least 500 times their diameter or thickness are commonly referred to as short or staple fibers meanwhile fibers with almost infinite length to diameter ratios are commonly referred to as long fibers or continuous filaments. Most often, this distinction is hardly encountered as most people prefer to just refer to both short fibers and continuous filaments as fibers [28].

Based on their origin, fibers can be classified as Natural or Synthetic (Man-made) fibers. Still on the basis of origin, these two categories can further be classified as in the figure below:

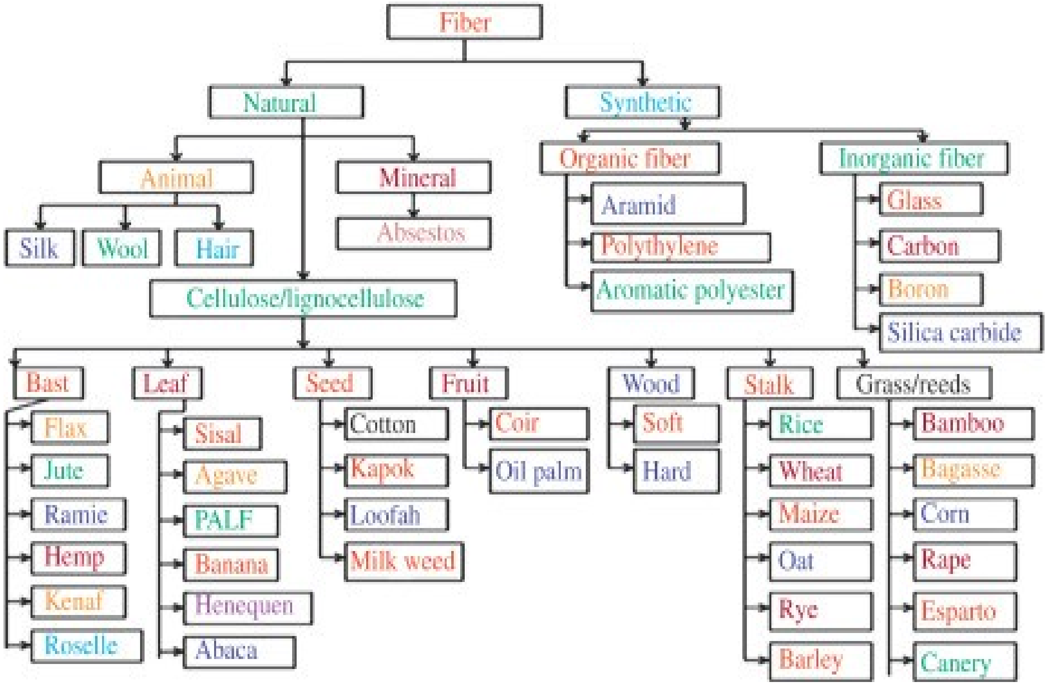


Figure 4: Classification of Natural and Synthetic Fibers [29]

2.4. Natural Fibers

Natural fibers are fibers that are extracted from natural sources such as plants, animals or minerals. Plant fibers are made up of bast, leaf or hard fiber, seed, fruit, wood, cereal straw and other grass fibers whose composition is based on cellulose or lignocellulose. Animal fibers include silk, wool and hair whose composition is based on protein. Meanwhile Asbestos is the naturally occurring fiber of mineral fibers [30].

The structure of most plant fibers is composed of cellulose, hemicellulose, lignin and waxes. Cellulose is a Polysaccharide (natural homopolymer) found in plant fibers with a relatively high modulus. Cellulose which is a homopolymer is connected to each molecule with a D-glucopyranose ring and glycosidic linkages. The main building blocks of plant natural fibers are chemical elements such as Carbon, Hydrogen and Oxygen which contain 65%-70% of cellulose [31]. Substances that do not contain cellulose are usually found in the cell wells and their presence tend to modify the final properties of the plant natural fibers. It is prohibitively expensive to completely eliminate the substances that do not contain cellulose from the plant natural fibers and as such almost every plant natural fiber contains non-cellulosic substances. Due to the hygroscopic nature of cellulose, plant natural fibers have a characteristic ability to absorb moisture from the atmosphere [32]. This property of plant natural fibers is responsible for the swelling in some polymeric fibers, alterations in weights and dimensions, as well as variations in strength and stiffness of plant natural fibers.

Lignocellulosic fibers are chemically composed of cellulose, hemicellulose and lignin and sometimes small amounts of wax, pectin and water-soluble substances [30,32]. Hemicellulose has a moisture content of about 2.6 times higher than lignin making it the second most abundant organic material [32]. Hemicellulose can either be homopolymers or heteropolymers primarily made up of anhydro-b-(1-4)-D-xylopyranose, mannopyranose, glucopyranose and galactopyranose main chains with some substituents [33]. The bond between cellulose and hemicellulose is noncovalent in nature but very strong and difficult to break. The constituent of hemicellulose in softwood is about 22%, while that in hardwood is about 26% and about 30% in various agricultural residues [33,34].

Lignin is a polymeric natural product which arises from dehydrogenative polymerization of three precursors (trans-sinapyl, trans-coniferyl and trans-p-coumaryl) usually initiated by an enzyme [34]. The difference in the quantity of the methoxyl groups ($AOCH_3$) usually present on the aromatic rings of lignin is what differentiate the different precursors. Lignin is found in the spaces between pectin, hemicellulose and cellulose in the cell walls of plant cells. Lignin is a three-dimensional polymer which is highly branched and composed of aromatic units [34]. It is partially covalently bonded with hemicellulose and covered in the cell wall of plants.

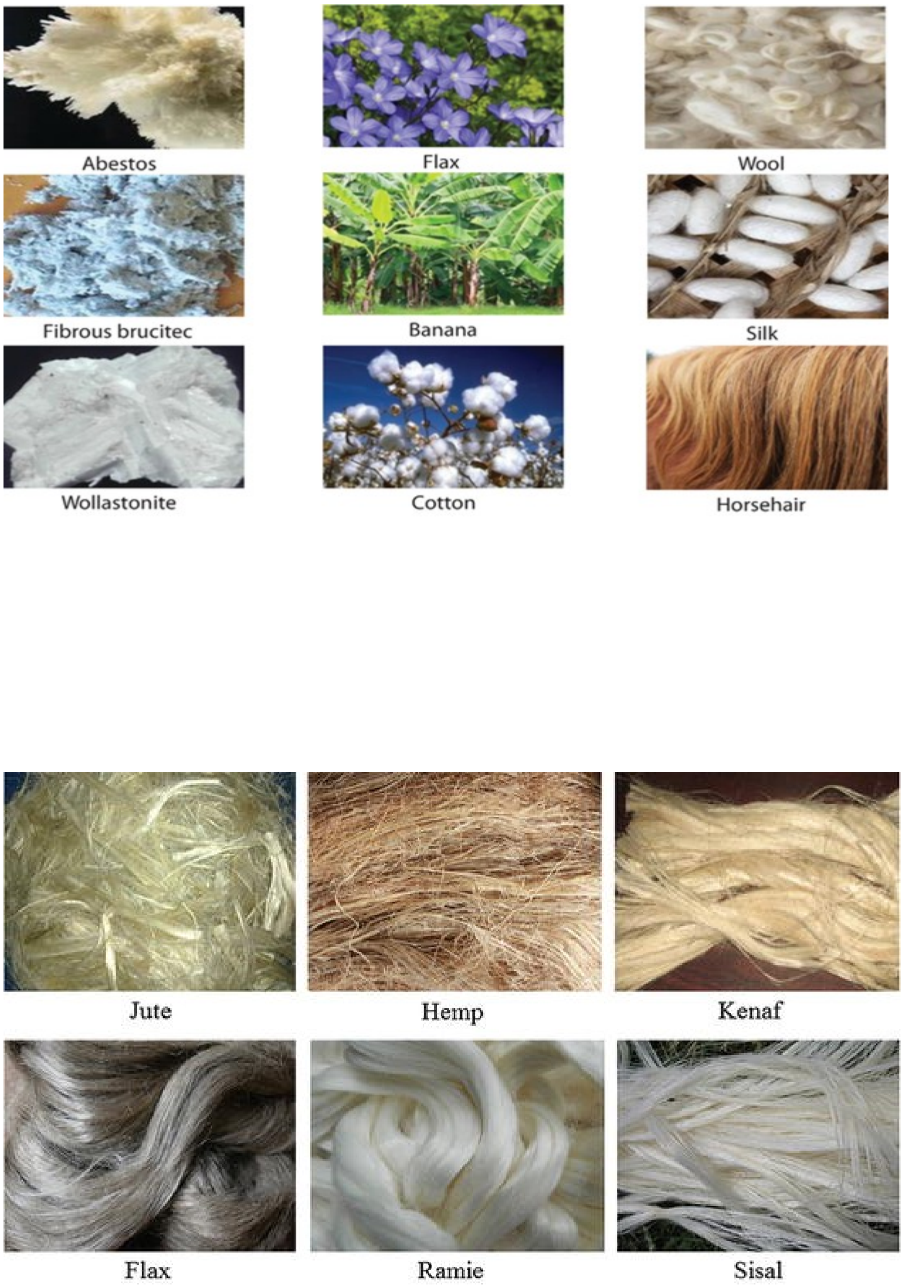


Figure 6: Some Selected Natural Fibers [35]

Table 1: Annual Production of Natural Fibers and their Sources [36]

Fiber Source	**World Production (10^3tons)**	**Origin**	**Fiber Source**	**World Production (10^3tons)**	**Origin**
Abaca	70	Stem	**Nettles**	Abundant	Stem
Bamboo	10,000	Stem	**Oil palm fruit**	Abundant	Fruit
Banana	200	Fruit	**Palm rah**	Abundant	Stem
Broom	Abundant	Stem	**Ramie**	100	Stem
Coir	100	Stem	**Roselle**	250	Stem
Cotton lint	18,500	Stem	**Rice husk**	Abundant	Stem
Elephant grass	Abundant	Stem	**Rice straw**	Abundant	Stem
Flax	810	Stem	**Sisal**	380	Stem
Hemp	215	Stem	**Sun hemp**	70	Stem
Jute	2500	Stem	**Wheat straw**	Abundant	Stem
Kenaf	770	Stem	**Wood**	1,750,000	Stem
Linseed	Abundant	Fruit	**Sugarcane bagasse**	75,000	Stem
Pineapple	Abundant	Leaf	**Cantala**	-	Leaf
Caroa	-	Leaf	**China jute**	-	Stem

2.5. Characterization of Natural fibers

The characteristics of natural fibers have been under investigation for more than two decades now. However, there are still some inconsistencies in the properties because of the different fibers used, different moisture conditions introduced and different characterization methods employed. Previous studies seem to agree that the properties of natural fibers depend on factors such as their structure, chemical composition, cell dimensions, microfibril angle, physical properties and mechanical properties. These properties differ considerably among different plant species and even in the same plant [37,38]. It is very important to understand the properties of natural fibers in order to make a reasonable and elaborate decision on their use for composites so as to improve their performance.

2.5.1. Physical Characterization

Cristaldi et al [39] and Huang et al [38] established that the physical properties of natural fibers are controlled by factors such as growing conditions of the fiber source, chemical composition, fiber ratio and processing method adopted for the extraction of the fiber. The physical properties of natural fibers are greatly affected by their individual materials which play a vital role in the choice of such materials for multidisciplinary applications. Fiber structure, microfibril angle, cell dimension and defects are very vital variables associated with the physical properties of natural fibers [40]. John and Thomas [34] stated that the origin, species, maturity and source of fiber are determined by the size of a single cell in a natural fiber. The Physical properties of natural fibers, particularly fiber length, fiber width and cell wall thickness are responsible for the properties of an end product such as tensile strength, tear strength, drainage, adhesion and stress distribution [41]. Also, the structure of the lumen affects the bulk density of fibers, which implicitly affect the thermal conductivity and acoustic factors of the end product of the fiber [42].

2.5.2. Chemical Characterization

Kumar et al. [43] stated that natural fibers are mainly composed of cellulose, hemicellulose and lignin, as well as small amounts of pectin, protein and ash. As we mentioned above, Cellulose is a semi-crystalline polysaccharide composed of D-anhydroglucose and glycosidic bonds. Cellulose offers strength, stiffness and structural stability to natural fibers which helps to maintain the plant structure and serve as a factor to determine its mechanical properties. Hemicellulose on the other hand is a branched polymer that is fully amorphous. Meanwhile lignin is a complex hydrocarbon polymer with both aromatic and aliphatic components. The table 2 below shows the variation in cell wall composition of natural fibers. The composition, structure and natural fiber properties depends on the age of the plant, conditions of the soil and other environmental conductions such as humidity, stress and temperature [44]. The Polymer chemistry of natural fibers greatly affects its properties, characteristics and functionalities [45].

2.5.3. Mechanical Characterization

Just like the physical properties, the mechanical properties of natural fibers are equally controlled by factors such as growing conditions of the fiber source, chemical composition, fiber ratio and processing method adopted for the extraction of the fiber. Studies have shown that properties such as the density, tensile strength, modulus of elasticity and other mechanical properties depend on the internal structure and chemical composition of the natural fibers. The modulus of elasticity of natural fibers decreases with increase in the diameter of the fiber [38]. Table 3 below shows the mechanical properties of some selected natural fibers while Table 4 shows the comparison between the mechanical properties of some selected natural and synthetic fibers.

Table 2: Chemical Properties of natural fibers [36]

Type of Fiber	**% Composition of Cellulose**	**% Composition of Hemicellulose**	**% Composition of Lignin**	**% Composition of Extractive**
Sisal	43.85-56.63	21.12-24.53	7.21-9.20	2
Oil Palm	44.20-49.60	18.30-33.54	17.30-26.51	4
Kapok	65.63-69.87	6.66-10.49	5.46-5.63	-
Bamboo	73	12	10	3
Corn Stalks	38.33-40.31	25.21-32.22	7.32-21.45	5
Banana	60.25-65.21	48.20-59.2	5.55-10.35	-
Abaca	69.23-70.64	21.22-21.97	5.15-5.87	-
Sugarcane (Bagasse)	55.60-57.40	23.90-24.50	24.35-26.30	10
Pineapple	70.55-82.31	18.73-21.90	5.35-12.33	-
Flax	69.22-71.65	18.31-18.69	3.05-2.56	6
Kenaf	37.50-63.00	15.10-21.40	18.00-24.30	6.4
Jute	69.21-72.35	12.55-13.65	12.67-13.21	4
Rice straw	28.42-48.33	23.22-28.45	12.65-16.72	17
Coconut (coir)	36.62-43.21	0.15-0.25	41.23-45.33	-

Table 3: Mechanical Properties of some natural fibers [36]

Type of fiber	Density (gm^{-3})	Tensile Strength (MPa¿	Young's Modulus (GPa)	Elongation at break (%)
Banana	0.65-1.36	51.6-55.2	3.00-3.78	1.21-3.55
Oil Palm	0.7-1.55	227.5-278.4	2.7-3.2	2.13-5.00
Bagasse	0.31-1.25	257.3-290.5	15-18	6.20-8.2
Corn stalks	0.21-0.38	33.40-24.80	4.10-4.50	1.90-2.30
Jute	1.3-1.45	300-700	20-50	1.69-1.83
Pineapple	1.25-1.60	166-175	5.51-6.76	2.78-3.34
Coconut (coir)	0.67-1.15	173.5-175.0	4.0-6.0	27.21-32.32
Rice straw	0.86-0.87	435-450	24.67-26.33	2.11-2.25
Sisal	1.45-1.5	300-500	10-30	4.10-4.3
Kapok	0.68-1.47	80.3-111.5	4.56-5.12	1.20-1.75
Abaca	1.42-1.65	879-980	38-45	9-11
Flax	1.27-1.55	500-900	50-70	2.70-3.6
Kenaf	0.15-0.55	295-955	23.1-27.1	1.56-1.78
Bamboo	0.6-1.1	360.5-590.3	22.2-54.2	4.0-7.0

Table 4: Mechanical Properties of some synthetic and natural fibers [46]

Fibers	**Tensile Strength (** MPa**)**	**Tensile Modulus (G**Pa**)**	**Specific Gravity**	**Specific Strength**	**Specific Stiffness**	**Failure Strength (%)**	**Price (** $Euro/Kg$¿
E-glass	2500-3500	70-73	2.56	27	29	2.5-3.0	1.5-2.5
Carbon	2500-6000	220-700	1.75-1.9	116	400	1.4-2	30-50
Flax	500-900	50-70	1.4-1.5	33	50	1.3-3.3	0.5-1
Sisal	80-840	9-22	1.3-1.45	6	17	3-7	0.3
Jute	200-450	20-55	1.3-1.4	14	42	1.16-1.5	0.12-0.5
Hemp	310-750	30-60	1.48	20	41	2-4	0.5-1
Banana	530-750	7-20	1.4	5	14	1-4	0.5
Coir	130-175	4-6	1.15	3	5	15-40	0.25
Cotton	300-600	6-10	1.5	4	7	7.0-8.0	1.6-4.6
Silk	-	-	1.34	-	-	-	18.3-36.7
Wool	125-200	-	1.31	-	-	-	Up to 15.4

2.6. Composites

Composites materials or mostly commonly called composites are a class of engineered (synthetic) materials consisting of two or more constituent materials with wide discrepancies in their physical, chemical and mechanical properties [47]. The overall properties of this class of materials are given by the individual properties of their constituents, their volume fraction and arrangement in the material system. The mechanical, structural and geometrical as well as aesthetic design requirements of composites depends on the type of application they are intended for. Composites find applications in Construction (buildings and bridges), automotive industry (car bodies), aerospace, naval (ships and boats) and medicine (biomedical engineering).

Generally, composites are classified into three major classifications as particle-reinforced, fiber-reinforced and structural composites [47]. Both particle-reinforced and fiber-reinforced composites can be further classified according to the type of matrix they have [Callister]. There are basically three major matrices that gives rise to polymer matrix composites, metal matrix composites and ceramic matrix composites. The summary of composite classification is presented in the figure below:

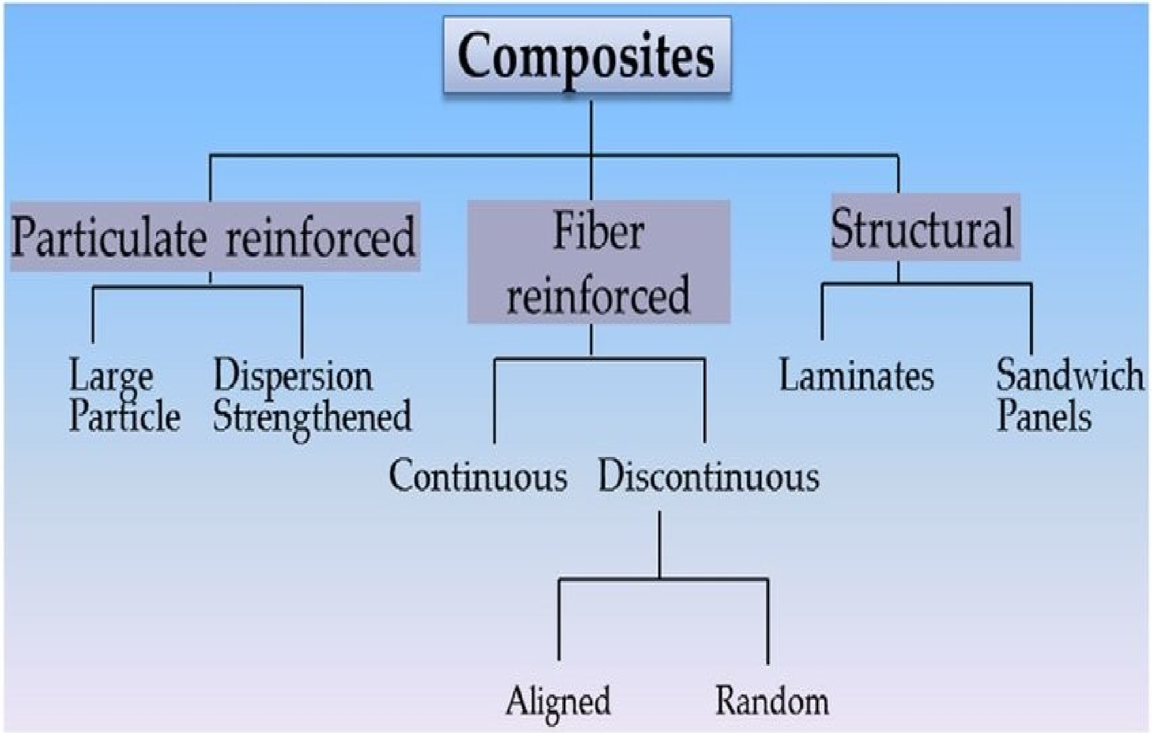


Figure 7: Classification of Composites [48]

2.6.1. Particle-Reinforced Composites

These are composites in which short particles are used as reinforcements. Based on the size of the particles used as reinforcement, they can further be classified into large particle-strengthened or dispersion-strengthened composites as represented by the figure below. In particle-strengthened composites, the large particles are usually in the order of millimeters or more in size and are usually the major load bearers. The particles equally help to prevent the matrix from deformation around their shared surfaces and this is the main strengthening mechanism in this kind of composites. Meanwhile in dispersion-strengthened composites, the particles are in the order of nanometers in size and the major load bearer is the matrix. The dispersed particles prevent the propagation of dislocation lines along the matrix and serves as the major strengthening mechanism. The value of the mechanical properties in these composites can be obtained by using the rule of mixtures [47].

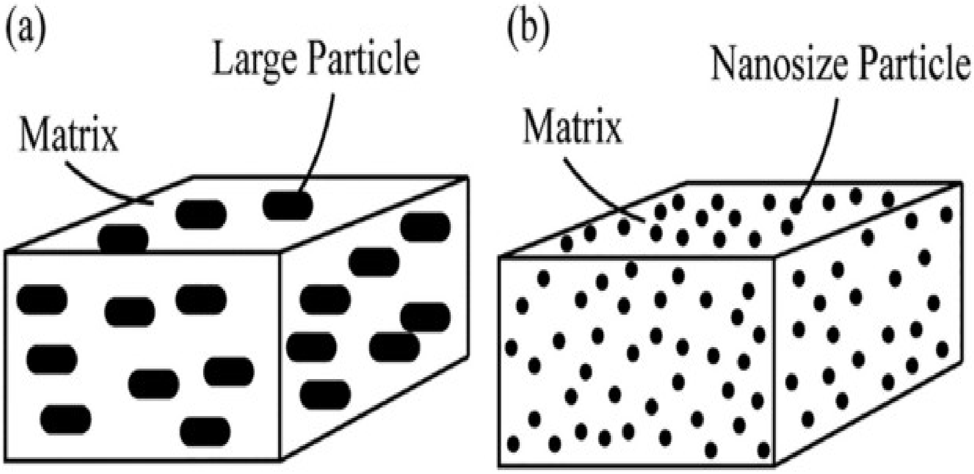


Figure 8: Particle-Reinforced Composites (a) Large Particle (b) Dispersion – Strengthened [47]

2.6.2. Fiber-Reinforced Composites

These are composites made by surrounding fibrous materials with attractive mechanical properties, with a matrix such as metal, polymer or ceramic. Fiber-Reinforced composites are the most widely known, fabricated and used composites. The length to diameter ratio of the fibers together with the individual properties of the constituents give rise to the strength and stiffness of the composites [49]. Fiber-reinforced composites are further classified into three groups depending on the length to fiber ratio and fiber orientation. This can be seen in the figure below:

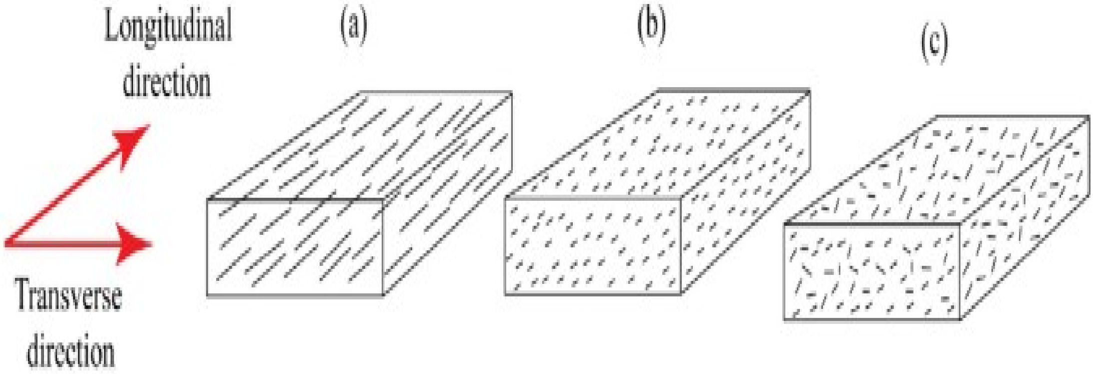


Figure 9: Fiber-Reinforced Composites (a) Continuous and aligned (b) discontinuous and aligned (c) discontinuous and randomly oriented [47]

2.6.3. Structural Composites

These are composites formed by carefully arranging a system of other composites and binding them with a homogenous adhesive material [50]. The mechanical properties, structural integrity and other properties of structural composites depends on the properties of the individual compositions of constituent composites and the geometry (shape and size) of the bulker structural constituent [51]. Laminar composites and sandwich panels are the two major categories of structural composites as shown in the figure below. A laminar composite is made by stacking two dimensional sheets having different preferred high strength directions together laminated by an adhesive. The sheets used are usually continuous and aligned fiber-reinforced composites. Meanwhile sandwich panels are usually made of a high strength exterior and relatively soft core held by a laminating agent. The outer sheets are often made of materials with high strength and stiffness such as plywood, steel and aluminum [52]. Most well-designed sandwich panels are capable of withstanding both compressive, tensile and shear stresses without failing. For high temperature applications, high temperature resistant adhesives are often used to prevent delamination.

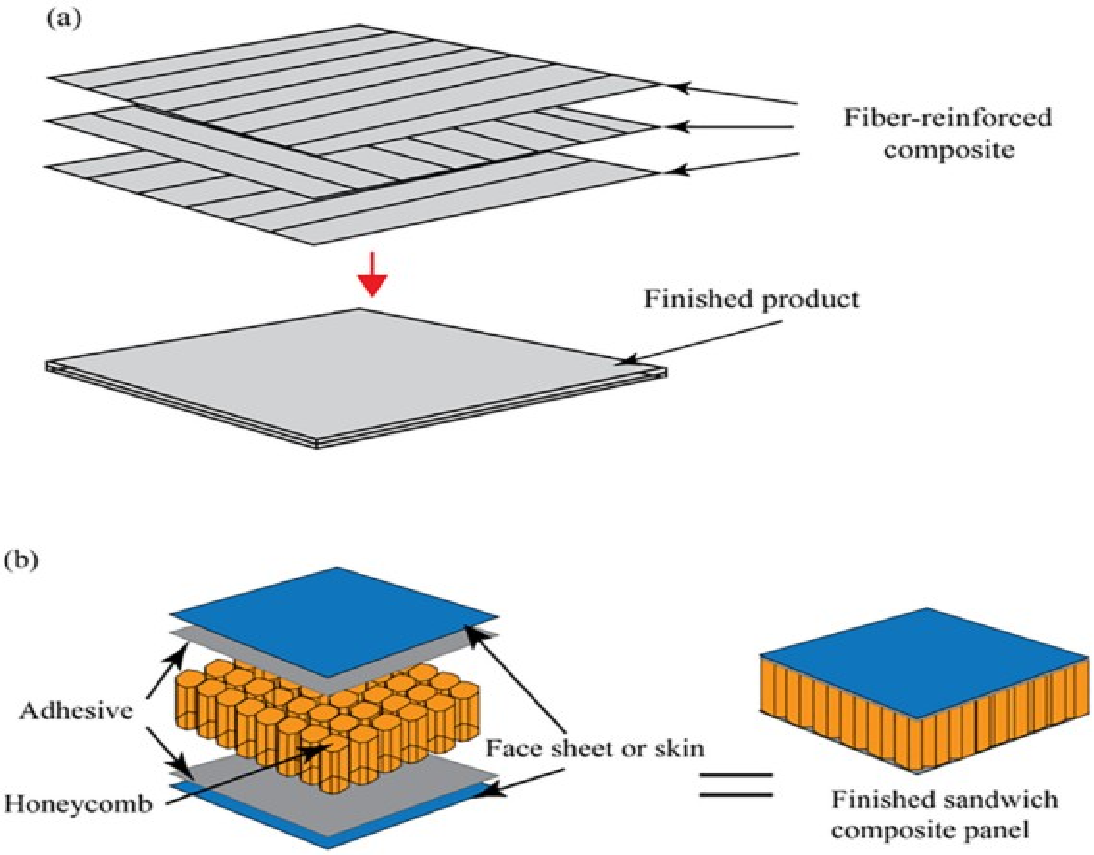


Figure 10: Structural Composites (a) Laminar composite (b) Sandwich Panel [47]

2.7. Gaps in Knowledge

From the available literature reviewed, FDM technique of AM is the most commonly used technique with a broad collection of applications. The FDM technique show attractive characteristics such as tensile force, compressive strength, dimensional precision, surface terminate hardness, ductility and production time. Not more than a few materials such as PLA, ABS, PET, PETG, TPU, PC, Nylon, ASA and ULTEM are used in the FDM technique of AM. However, new materials are being explored. In recent years, research is being carried out and focus is on optimizing process parameters and improving properties such as mechanical, thermal and surface roughness properties as well as reducing material wastage and build time of the product for FDM techniques of AM. Different researchers are exploring diverse approaches of improving the range of melting temperature for getting good surface finish in the FDM technique. Presently, PLA and ABS are widely used materials for the FDM technique due to its commercial availability at low cost. Other people use different materials in view of improved thermal and mechanical properties of products.

Although research is being conducted on AM, very little has been carried out under different environmental conditions of temperature, humidity and noise. In recent years, further research is focused on composites materials such as polymer-metal and bio-composites. Most often metal powders of aluminum and iron are used as reinforcements in the polymer matrix. Other kinds of filler materials and abrasives are equally being used. Due to an increase in environmental pollution, natural fiber-reinforced composites show potentials of replacing glass fiber reinforced composites.

Researchers in the FDM techniques of AM have shown that properties such as tensile strength, microhardness and percentage elongation of materials are different for different reinforcement ratios. However, not much has been said about the wear rate, coefficient of friction and specific wear rate of the composites for different ratios of reinforcement. It will be a great thing to produce a functional composite for FDM technique of AM without compromising its mechanical and wear properties.

CHAPTER THREE

3.0. RESEARCH METHOD

In an attempt to answer some of the scientific questions and meet the research objectives of this Thesis, the following methodology was adopted:

3.1. Sample Preparation

Computer Aided Design (CAD) files of an automobile body, car door, wheel rim and tensile test specimen of ASTM-638-TYPE-IV were prepared in Standard Tessellation Language (STL) format for 3D printing using a computer. The CAD files were 3D printed using the Lulzbot Taz 6 3D printer at AUST with Poly lactic acid (PLA) as the printing filament.

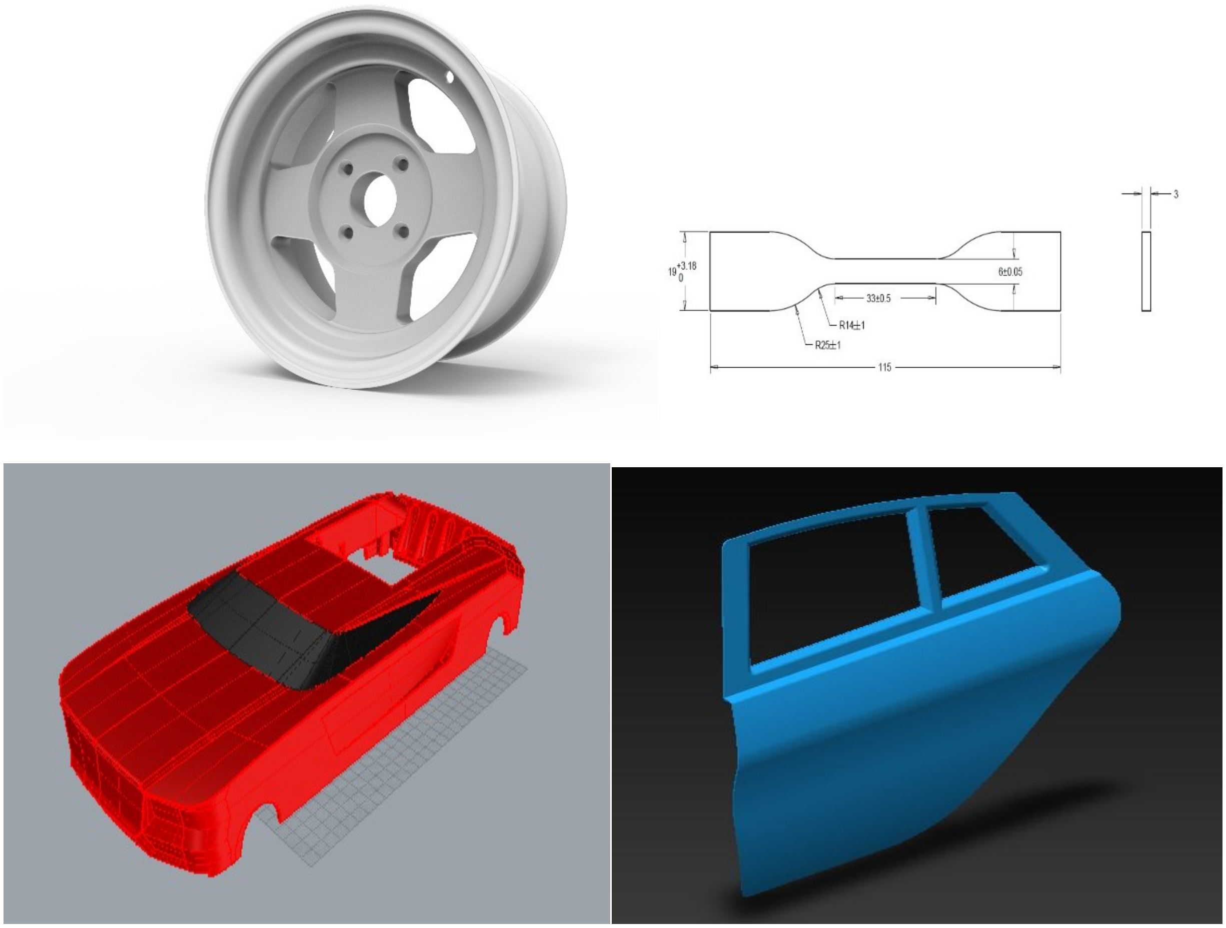


Figure 11: CAD Files for 3D Printing

3.2. Scanning Electron Microscopy (SEM)

Portions of the 3D printed materials were cut off and polished using a polishing wheel at AUST. After polishing, they were coated with Gold using a coating machine at AUST. The reason for coating the samples was to make them conducting so that the backscattered electrons in the SEM instrument can effectively reveal the microstructures of the samples. The samples were then mounted on a stage in the vacuum chamber of the SEM instrument and micrographs of the samples were taken at 20 μm and 100 μm.

Figure 12: Scanning Electron Microscopy (SEM) Test

3.3. Mechanical Characterization of Sample

The samples were prepared and investigated for their mechanical properties as follows:

3.3.1. Tensile Strength

Four tensile test specimens of ASTM-638-TYPE-IV with gauge lengths of $40\,mm$, widths of $6\,mm$ and diameters of $4\,mm$ were 3D printed using the Lulzbot Taz 6 3D printer at AUST at different printing speeds. The printing conditions of the four specimens are summarized in the following table:

Table 5: Printing Conditions of Tensile Test Specimen

Specimen	**Nozzle Temperature (** ℃¿	**Bed Temperature (** ℃¿	**Printing Speed (** mm/s¿	**Printing Time (** *seconds*¿
1	205 - 210	60	60	1399
2	205 - 210	60	55	1493
3	205 - 210	60	50	1657
4	205 - 210	60	45	1762

Tensile tests were carried out on the test specimens using the Instron Universal Testing Machine at AUST. The cross-head speed of the instrument was set at $5\,mm/s$. Below are images of the process:

Figure 13: Tensile Test

3.3.2. Modulus of Elasticity

Data obtained from the tensile test was plotted using a software known as Origin Lab Pro. The slope of the Tensile Stress (MPa)against extension ¿) was determined and this corresponds to the Modulus of Elasticity of the 3D printed material.

3.3.3. Ductility

To determine the ductility of the 3D printed materials, the percentage elongation reported in the tensile test experiment was calculated for each sample as follows:

$$Ductility = Percentage\ Elongation$$

$$Percentage\ Elongation = \frac{final\ gage\ length - initial\ gage\ length}{initial\ gage\ length}$$

$$\therefore Ductility = \frac{l_f - l_0}{l_0} \times 100$$

3.3.4. Hardness

To determine the hardness of the 3D printed material, samples were cut out of the 3D printed materials and characterized using the Hysteron Nanoindentation system (Tribo TI 950) at AUST with a Diamond probe. The samples were loaded using a trapezoidal load function inbuilt in the Nanoindentation system having both a loading with an unloading segment.

3.4. Environmental Impact Assessment

A life cycle assessment was performed to determine the environmental impact of these new materials and method of manufacture for automotive applications both in service and at the end-of-life use. This was done by way of comparison of the mechanical properties obtained for the new materials with those currently being used in the industry. Also, additive manufacturing as new method of manufacturing was contrasted with current manufacturing techniques.

CHAPTER FOUR

4.0. RESULTS AND DISCUSSION

The following results were obtained:

4.1. Proof of Concept

The results of the 3D printing of the CAD Files of some automobile parts that were prepared are as shown in Fig. 14.

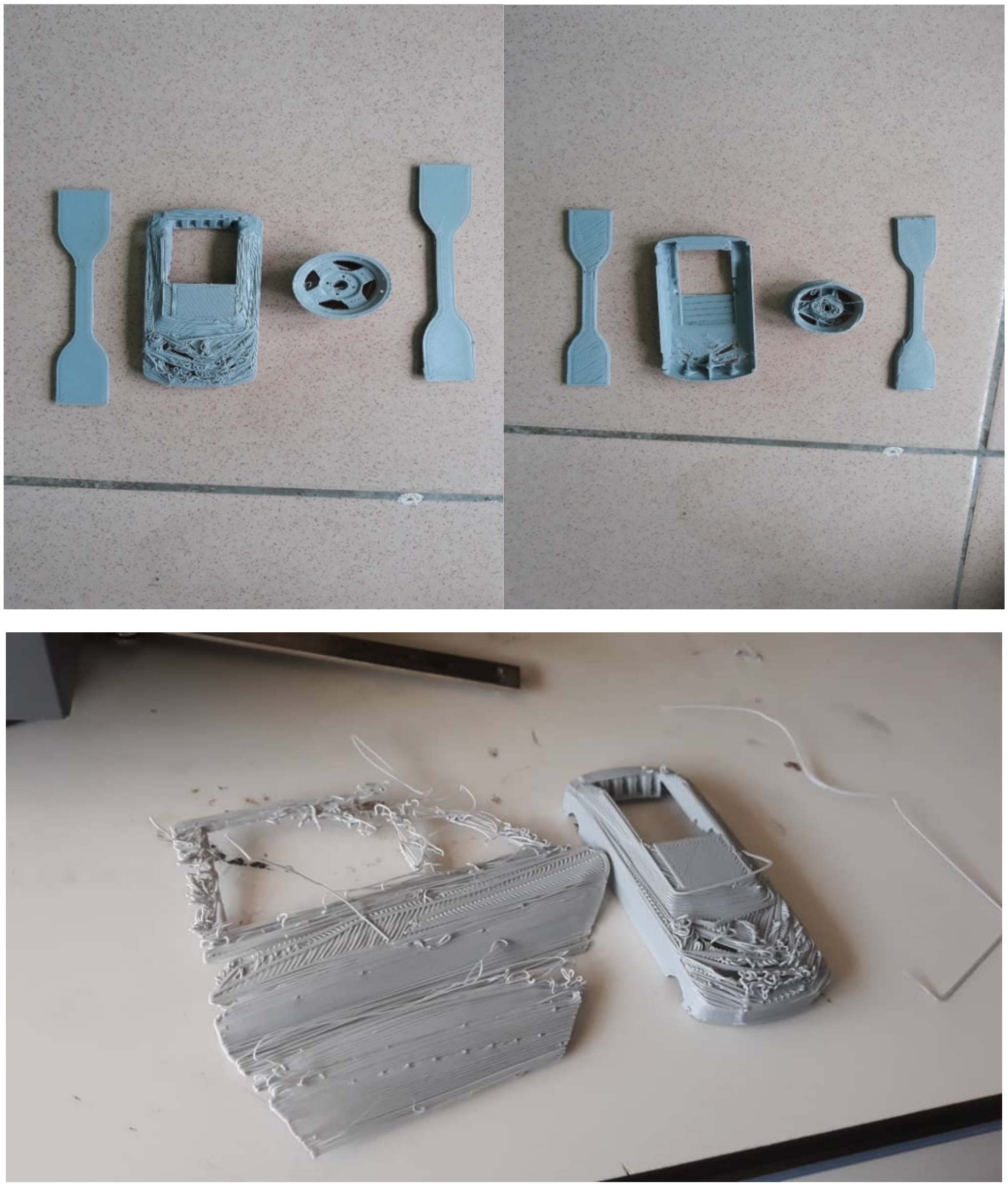


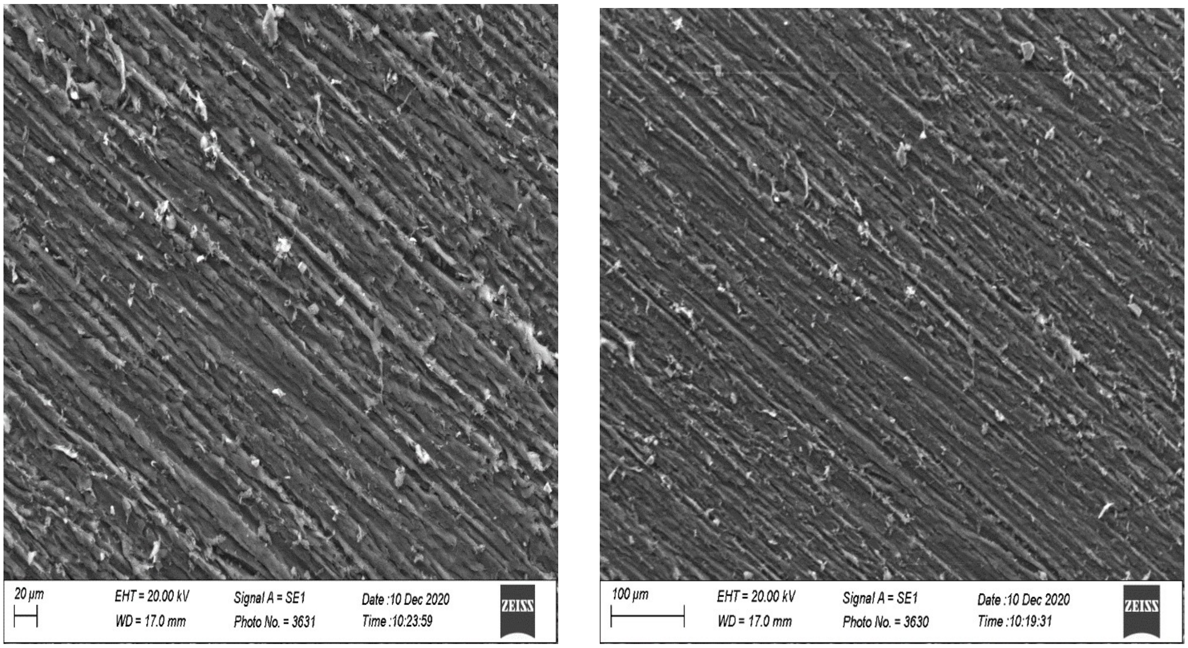
Figure 14: 3D Printed Materials

These results demonstrated that if scaled up, additive manufacturing can be applied in the production of automobile parts of comparable nature and strength as those produced by conventional methods. The printing of these automobile parts in the context of this work witnessed some impactions especially in areas where the print had no support from the bed of the printer due to the inability of the Lulzbot Taz 6 3D printer to print in a hexagonal fashion. However, if more efficient and robust 3D printers, with the capability of printing in a hexagonal fashion are used, these imperfections will be eliminated.

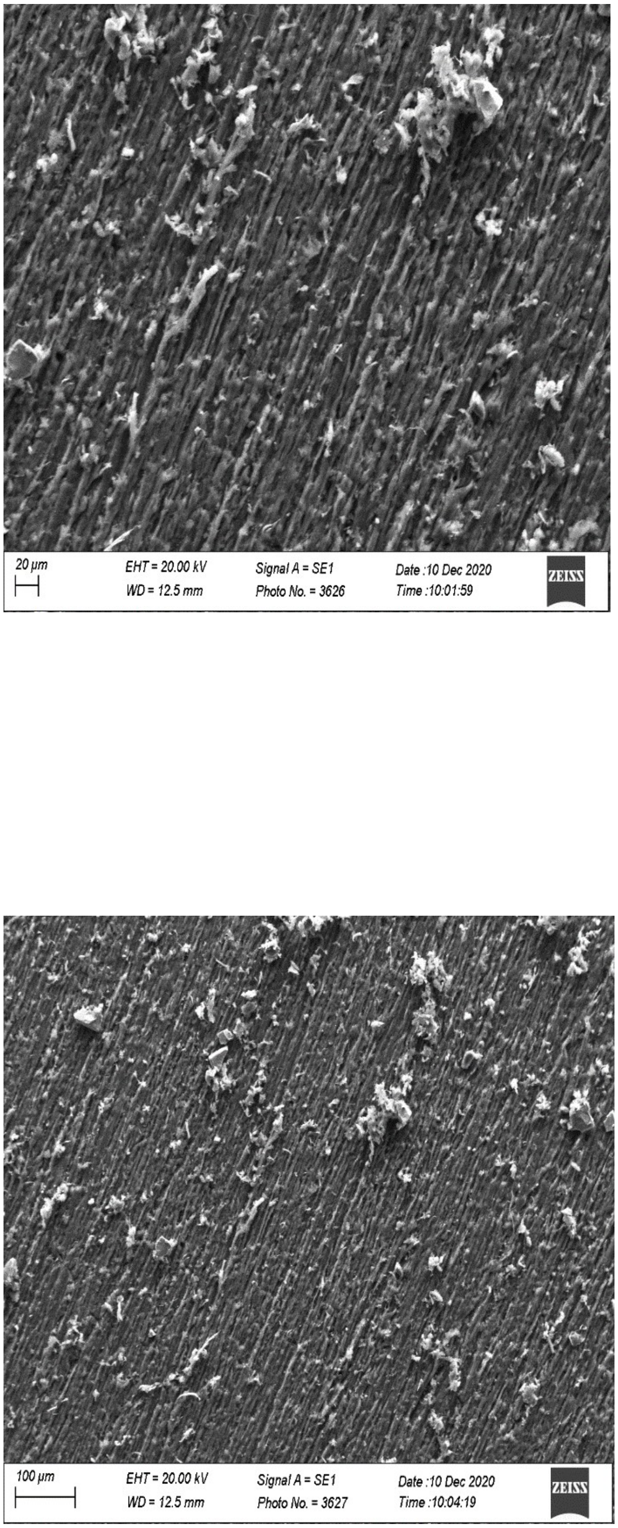
4.2. Scanning Electron Microscopy (SEM)

The micrographs of the 3D printed materials that were obtained are as shown in Fig 15.

These micrographs revealed that there is close packing within the 3D printed materials with little or no voids associated with the design of the CAD file and the time it takes for one layer of the filament to cure while the other is being deposited. The lines on the surfaces of the micrographs arise from the polishing of the samples during preparation.



(a) Sample 1


20 µm
EHT = 20.00 kV
WD = 12.5 mm
Signal A = SE1
Photo No. = 3626
Date :10 Dec 2020
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ZEISS
100 µm
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Signal A = SE1
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Date :10 Dec 2020
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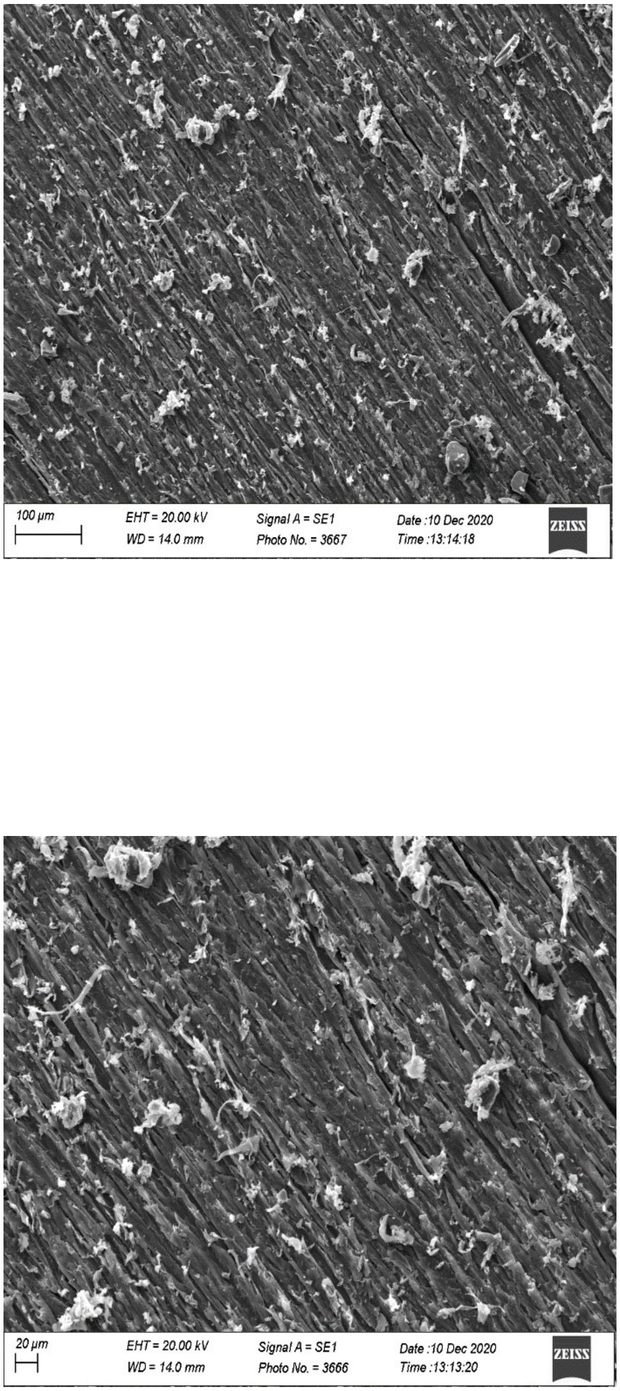
(b) Sample 2


100 µm
EHT = 20.00 kV
WD = 14.0 mm
Signal A = SE1
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Date :10 Dec 2020
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20 µm
EHT = 20.00 kV
WD = 14.0 mm
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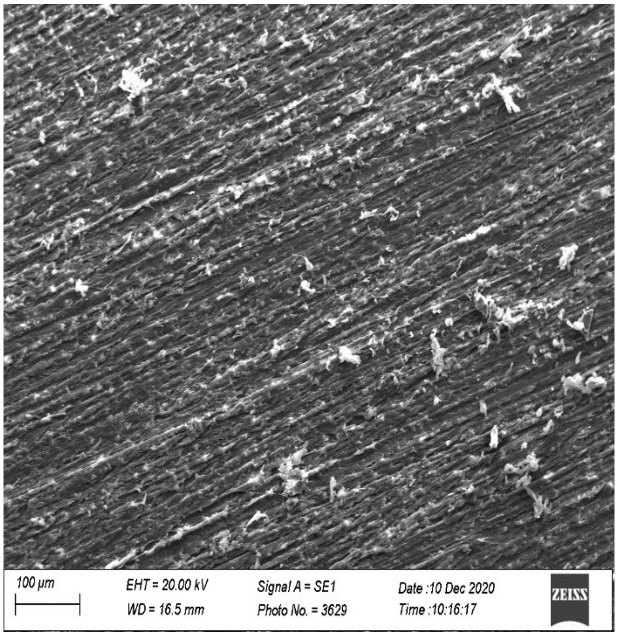
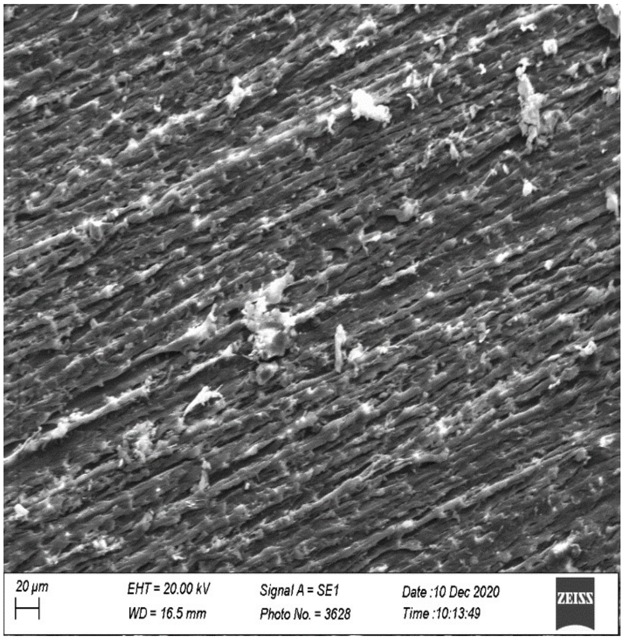
(c) Sample 3





(d) Sample 4

Figure 15: SEM Results

4.3. Mechanical Characterization

The results of the mechanical characterization of the 3D printed materials are as shown:

4.3.1. Tensile Strength

The profile of the tensile stress (MPa) against extension (mm) curve of the 3D printed specimens showed that three major regimes exist when polymeric 3D printed materials are loaded as follows:

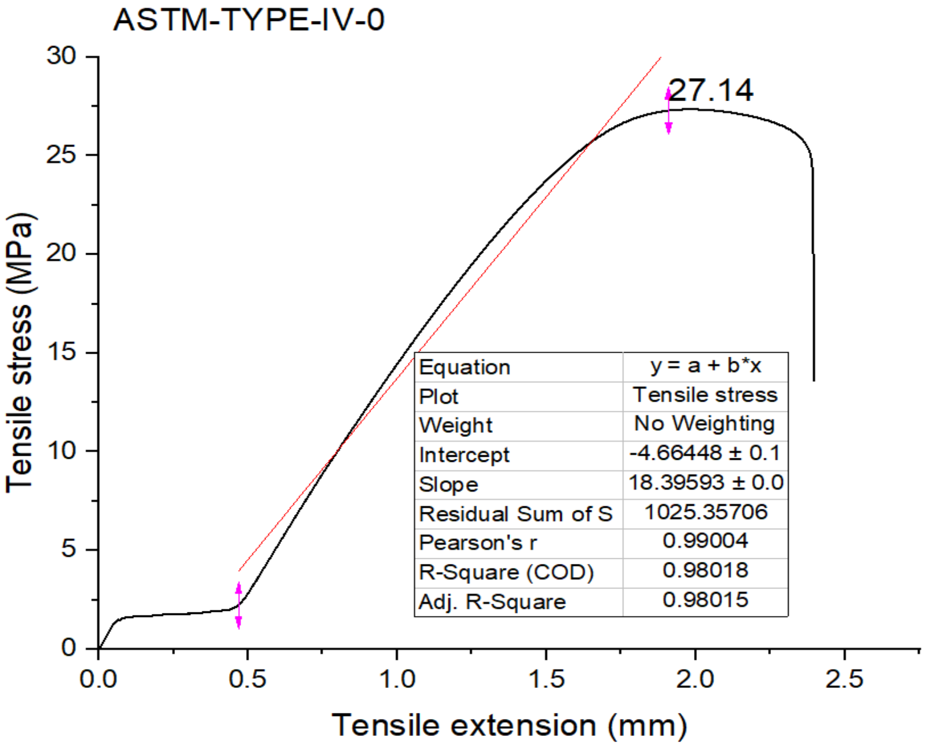
- A linear regime where the extension is directly proportional to the applied stress
- A yielding regime where the materials experience plastic deformation and
- A fracture regime where the material can no longer bear the load applied on it.

This is expected since we are dealing with a polymer.

The four specimens showed that the 3D printed materials have an average Ultimate Tensile Stress (UTS) of $25.57\ MPa$ which corresponds to the strength of the materials. It was equally observed that the UTS of the 3D printed materials fairly decreased with an increase in the printing speed. Table 6 summarizes the strength values of the 3D printed specimens:

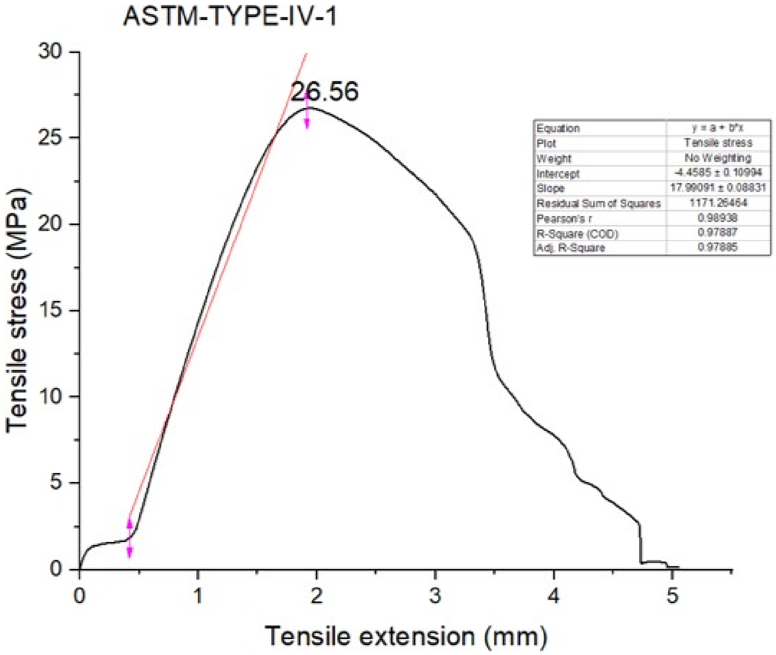
Table 6: Tensile Strength Values

Specimen	**Tensile Strength** (MPa)
1	27.14 ± 0.10
2	26.56 ± 0.08
3	27.23 ± 0.01
4	21.33 ± 0.10



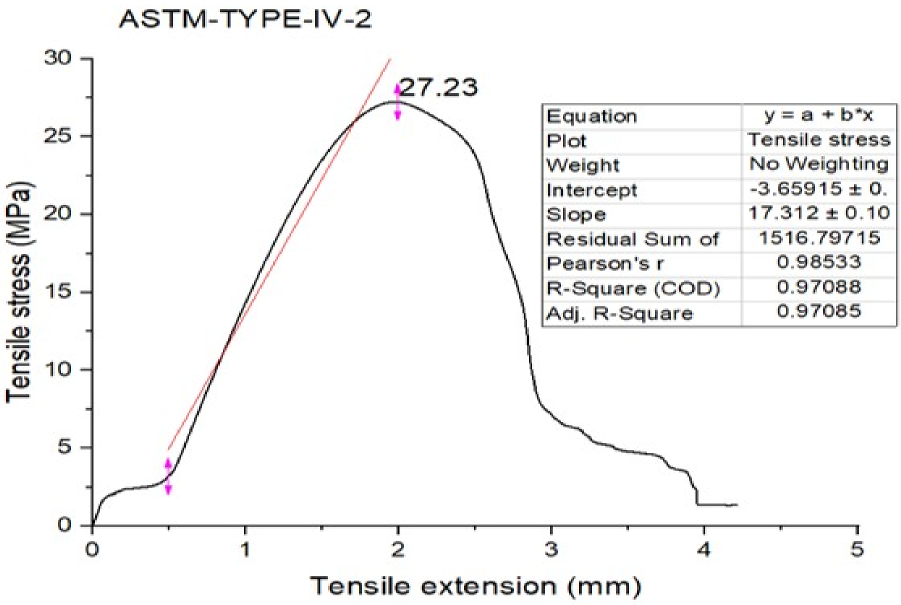
Equation	y = a + b*x
Plot	Tensile stress
Weight	No Weighting
Intercept	-4.66448 ± 0.1
Slope	18.39593 ± 0.0
Residual Sum of S	1025.35706
Pearson's r	0.99004
R-Square (COD)	0.98018
Adj. R-Square	0.98015

(a) Sample 1

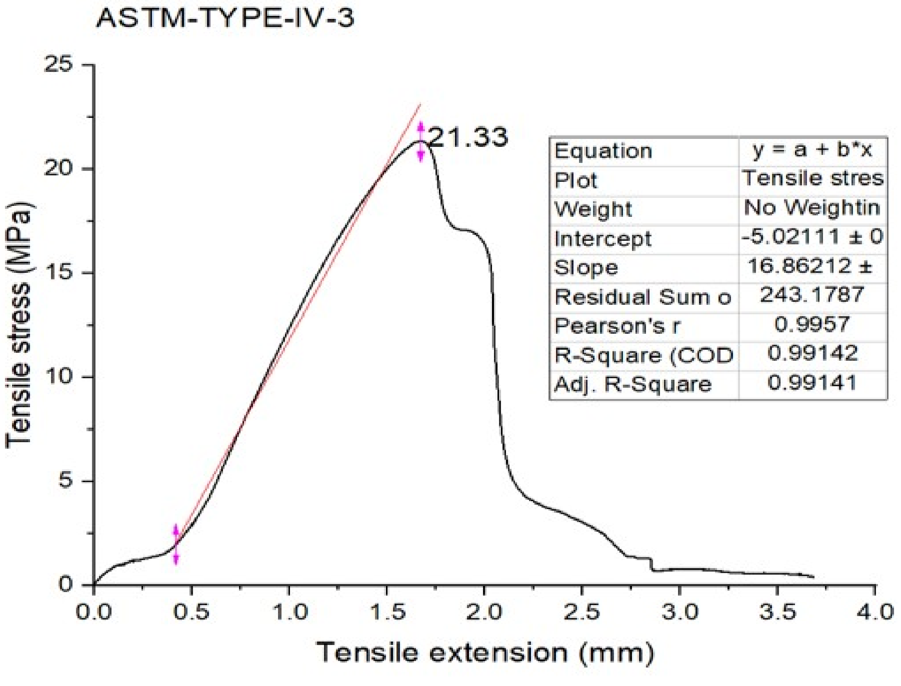


Equation	y = a + b*x
Plot	Tensile stress
Weight	No Weighting
Intercept	-4.4585 ± 0.10994
Slope	17.99091 ± 0.08831
Residual Sum of Squares	1171.26464
Pearson's r	0.98938
R-Square (COD)	0.97887
Adj. R-Square	0.97885

(b) Sample 2



(c) Sample 3



(d) Sample 4

Figure 16: Tensile test Results

-

4.3.2. Modulus of Elasticity

The Slope of the Tensile Stress (MPa) – Extension (mm) curve showed that the Modulus of Elasticity of the four specimens were as shown in Table 7.

Table 7: Modulus of Elasticity Values

Specimen	**Modulus of Elasticity (MPa)**
1	18.396 ± 0.00
2	17.991 ± 0.08
3	17.312 ± 0.10
4	16.862 ± 0.00

Averagely, the Modulus of Elasticity of the 3D printed materials was found to be $17.640\,MPa$.

4.3.3. Ductility

From the profile of the tensile test experiment, we can see that the 3D printed materials demonstrate some degree of ductility since all the specimens suffered yielding or plastic deformation before fracture. The values calculated for the ductility are shown in Table 8.

Table 8: Ductility Values

Specimen	Ductility (%EL)
1	6.75
2	12.25
3	11.0
4	9.25

4.3.4. Hardness

The Hysteron Nanoindentation system (Tribo TI 950) at AUST broke down and we were unable to obtain these results from the system to make analysis on how these materials will behave in a crash scenario. As such, we have included it in the recommendations for future work.

4.4. Environmental Impact Assessment

Making an Environmental Impact Assessment (EIA) showed that 3D printing as technique for the manufacture of automobile parts is a promising technology capable of reducing the carbon dioxide content in the atmosphere since less energy is required when compared to other techniques of manufacture such as injection molding. Also, the EIA showed that at the End of Life (EOF) use, these 3D printed materials can be recycled to extrude filaments that can be again used in the 3D printing of other materials with comparable mechanical properties. Poly Lactic Acid (PLA) Polymers generally are biodegradable just as natural fibers which makes application of composites from these constituents environmentally friendly.

CHAPTER FIVE

5.0. CONCLUSION, LIMITATIONS AND RECOMMENDATIONS

5.1. Conclusion

In this work, we were able to show that the application of additive manufacturing in the automotive industry is possible and is capable of producing lightweight structures with enhanced mechanical properties comparable to those of conventional materials in use. This will go a long way to mitigate the effects of climate change due to carbon dioxide emissions since Additive manufacturing has a lower energy requirement and 3D printed materials are recyclable at the End-of-life use and some are equally biodegradable.

5.2. Limitations

This work suffered some setbacks which made the realization of some of our objectives difficult. Some of these setbacks include:

1. The inability of our Lab to secure an extruder in time from which Natural Fiber Reinforced Polyethylene Terephthalate (NFRPET) filaments could be extruded for the 3D printing of materials of these composites. Hence, our inability to present the results of the characterization of 3D printed materials of these composites.
2. We indented to investigate the hardness of our 3D printed materials using the Hysitron Nanoindentation system (Tribo TI 950) at AUST with a diamond probe to determine how they will behave in a crash scenario but were unable to do so due to a breakdown of the system.

5.3. Recommendations

We recommend that future research should focus on the following:

1. Extrusion of natural fiber reinforced polymer filaments for 3D printing and the characterization of the 3D printed materials of these filaments.
2. Investigation of the interfacial bonding in natural fiber reinforced polymer composites for 3D printing and how the bonding can be enhanced.

3. Environmental Impact assessment of these composite by way of simulation of the properties obtained from the characterization.

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