

Chapter 15-MAT 102: Overview of Materials Engineering

ADELEKE Abraham Adewale, *Obafemi Awolowo University, ALABI AbdulGaniyu F.*, *Kwara State University* and **MUSTAPHA Kabiru**, *Kwara State University*

Overview

Materials Engineering, the engineering sub-discipline of materials science and engineering uses the knowledge of metallurgy and materials science in the extraction, development, and processing of metals, ceramics, polymers, and composites. It uses traditional metallurgy techniques and the emerging materials science technologies such as thermomechanical processing, additive manufacturing, and nanofabrication to produce new materials with superior physical and mechanical properties for advanced engineering applications. Materials engineering from a developing nation's perspective, emphasizes the addition of values to local primary natural resources and seeks to extend their applications to satisfy advanced engineering requirements such as in the production of aircraft, spacecraft, automobiles, and biomedical engineering components. It uses the concept of material-enabled design to produce appropriate materials that will satisfy the requirements of performance, reliability, and cost; thereby promoting product success in service through the reduction in instances of material failure.

Objectives

After reading this chapter, students should be able to:

1. Distinguish between materials engineering and other related disciplines.
2. Describe the evolution of metallurgy over the centuries to become materials science and engineering today.
3. Recognise materials engineering as a specialisation in materials science and engineering.
4. Narrate the origin of formal mining and metal extractions in Nigeria.
5. Categorise materials as metals, polymers, ceramics, and composites.
6. Describe typical techniques to process raw materials, metals, ceramics, and polymers.
7. Explain the roles of emerging technologies like nanofabrication and additive manufacturing in producing advanced materials and functional products.
8. Describe thermomechanical rolling and its effects on the properties of rolled products.
9. Explain the purpose of metal surface finishing processes like coating, electroplating etc;
10. Describe the techniques of metal surface finishing such as electroplating and electropolishing.
11. Enumerate the criteria required to select appropriate materials for engineering applications.
12. List the different types of heat treatment methods.

What is Materials Engineering?

Materials engineering has its origin in metallurgy which refers to the science and technology of extracting metals from primary and secondary sources and processing them into various alloys and products. On the other hand, materials engineering encompasses metallurgy and extends its emerging techniques of materials science to the processing of metallic and non-metallic materials. The better-engineered products of materials engineering find applications in sectors such as building construction, and manufacturing of automobiles, aircraft, and spacecraft. In addition to the conventional metallurgical processing to extract metals like aluminium from their primary ores such as bauxite and form them into products, a materials engineer uses emerging technologies to extend the range of products obtainable from primary raw materials. For instance, he can start from bauxite ore and proceed to produce composites such as $\text{Al}_2\text{O}_3\text{-SiC}$, aluminum matrix composites (AMC), and deposit thin films of alumina and aluminium on components by sputtering and co-sputtering. Using emerging techniques of additive manufacturing like Laser Powder Bed Fusion (LPBF) he processes conventional high-strength aluminum alloys (HSLA) further to complex metal components. Furthermore, metals like titanium, tantalum, and cobalt are processed by materials engineers working with researchers from health sciences to produce biocompatible implants such as blood tubes, sutures, and bone plates.

In scope, materials engineering requires courses like materials science, mineral processing, crystallography, extractive, chemical, physical, and mechanical metallurgy. Furthermore, engineering science courses like fluid mechanics, mechanics and strength of materials, chemical engineering, and metallurgical thermodynamics as well as corrosion science are also essential to understand the discipline. Design and processing diagrams like Ellingham, Pourbaix, and predominance area diagrams are important tools of materials engineering. Extraction techniques such as smelting, refining, electrolysis, contact reduction, and hydrogen reduction also play key roles in materials engineering.

History of Materials Engineering

In history, mankind has passed through different stages or ages of development which were largely dependent on the type and versatility of the materials available to him. Metallurgy, the origin of materials engineering transited mankind from the stone age which was characterised using stones and potteries to the bronze age, when bronze, the alloy of copper and tin became the hardest common material available to man for weapons, tools, and armor production. Mankind was again taken from the brass age to the iron age. The glass age succeeded the iron age and metallurgy further took the man to the steel and aluminum age from around 1800s. While the products of metallurgy remain useful to mankind, further developments in materials processing led to the production in 1862 of the first artificial plastics by Alexander Parkes, a metallurgist. Plastics then began to compete with metals in many applications. The late 20th century to the early 21st century has been described as the silicon, information, or digital age of man because of the large impact of silicon in producing semiconductors for computers and other devices for information technology (Smith, 2019). The period also witnessed striking advances in the field of materials science that investigates the structure and properties of materials to design and produce new functional materials of superior physical and mechanical properties for new devices in advanced engineering applications.

History of Mining and Metallurgy in Nigeria

The mining sector accounts for only about 0.3% of Nigeria's Gross Domestic Product (GDP) despite the abundance of various solid minerals across Nigeria. Mining activities in a coordinated manner started in Nigeria between 1903 and 1904 when the British Colonial Government established the Mineral Surveys of Northern and Southern Protectorates. By the 1940s, Nigeria was a major mining and supply source for tin, columbite, and coal. Cassiterite mining was pioneered by the British Royal Niger Company in Berom land in Plateau State. Tin production in Nigeria was put at 6,910 tons in 1915 and it grew to 10,596 tons in 1960 (Dalyop, 2018). Before the advent of the British, local cassiterite mining and smelting were done in places like Lireuin and Delma in Northern Nigeria. However, in 1962, a British Company, Consolidated Tin Smelters established the Makeri Smelting Company Limited in Jos to produce tin metal (Abubakre *et al.*, 2009).

To develop the iron and steel sector, from around 1979, the Federal Government began the process to establish the blast furnace based Ajaokuta Steel plant, the Midrex based Delta Steel plant, Aladja, and the three inland rolling mills at Osogbo, Jos, and Katsina. While the Delta Steel plant was completed in 1980 and operated to supply steel billets for processing at the inland rolling mills, Ajaokuta Steel plant's blast furnace to produce liquid iron is yet to be completed to date.

Introduction to Modern Materials

Identification of Materials

Materials are identified based on their structures (atomic and crystallographic), chemical composition, process of manufacturing, and engineering applications. Based on these factors, materials can be generally classified as metals, ceramics, polymers, composites, and advanced materials.

Metals and Alloys

These are materials whose atoms have free valence electron(s) in the outermost shells. These valence electron(s) are responsible for their good thermal and electrical conductivities. They are ductile with relatively high stiffness, toughness, and strength. They can be taken through processes such as machining, casting, forming, stamping, and welding to be shaped for industrial purposes. However, they are prone to corrosion. Metals find applications in structures, automobiles, machine tools, electrical wiring, etc. Examples of native metals are gold and platinum, while other metals include iron, aluminium, and copper. Steel is an alloy of iron and carbon with minor contents of other elements such as silicon and manganese, while copper is alloyed with tin and zinc to produce bronze and brass, respectively.

Metal alloys are produced as solid solutions of combinations of metallic and some non-metallic elements. Ferrous alloys, comprising steel and cast irons, are produced with iron as the base material serving as the solvent in the liquid state and carbon with smaller proportions of other elements such as manganese as alloying elements. Carbon is the primary solute element in iron for steelmaking and it increases steel's hardness and strength but reduces its ductility and weldability. Plain carbon steels are sub-divided into low, medium, and high carbon steels with carbon contents of less than about 0.30%, 0.30 to 0.70%, and 0.70 to 1.4%; respectively. Low-carbon steels exhibit low strength but high ductility and can be easily welded. Since it has a low carbon content, its strength can only be increased by cold working and not by heat treatment. (MCI, 2023).

Low alloy steels refer to ferrous alloys with combined alloying elements less than about 8%. They have better strength and resistance to corrosion than carbon steel. Some low-alloy steels designed to obtain better mechanical strength are called high-strength low alloy steels. Stainless steels are ferrous alloys with a chromium content of at least 12% and other elements such as nickel, silicon, and manganese at varying contents. The high content of chromium causes the steel to passivate in a corrosive environment and thus resist corrosion effectively. Stainless steels are classified as ferritic, austenitic, martensitic, and duplex stainless steels. Austenitic stainless steels are used for structures such as pressure vessels that operate in severe corrosive conditions (MCI, 2023).

Cast irons are ferrous alloys with carbon contents higher than 2% and unlike steel that has its carbon as only iron carbide, the carbon in cast irons can exist in the iron matrix either as graphite flakes or carbide and are called grey or white cast irons, respectively. When grey cast iron is inoculated with magnesium or cerium, the graphite flakes are converted to nodules of spherical shapes, and such cast irons are called ductile or nodular cast irons. Ductile irons exhibit higher strength, ductility, and machinability. Cast irons are easily melted and cast into large-sized intricate shapes than steels (MCI, 2023)

Pure aluminium exhibits low density and good resistance to corrosion but low hardness and strength but it can be alloyed with other elements such as manganese, copper, and silicon to obtain increased strength and hardness. Nickel alloys have nickel as the base metal while elements such as chromium and molybdenum are added to produce nickel alloys that exhibit exceptional strength and resistance to corrosion and scale formation at elevated temperatures. Nickel alloys also demonstrate unique properties such as low coefficient of expansion and shape memory characteristics that enable them to regain their original shape on heating. Titanium alloys are very expensive and find applications in the aerospace industry because of their low density and good strength-to-weight ratio. They are produced when titanium is alloyed with elements such as aluminium, tin, and vanadium. As of 2022, the world's output of steel was about 1.29 billion tons, while the annual output for aluminium and its alloys that ranked next to steel for structural applications was above 62 million tons (Sengupta, 2023).

Ceramics

These are compounds formed from the combination of metallic and nonmetallic elements. They are usually oxides (Al_2O_3 , SiO_2 , MgO , etc.), carbides (SiC), borides (TiB_2), and nitrides (Si_3N_4). Ceramic materials are hard, brittle, and dense or light weight based on the technique of formation. They have high strength, low electrical conductivity, and high thermal and corrosion resistance. Ceramic materials find applications as electrical and thermal insulators, coatings, corrosion-resistant materials, building blocks (bricks), biocompatible materials, etc. Ceramics are classified as refractory (magnesite), abrasive (diamond), engineered (silicon carbide), and cermets (MCI, 2023).

Polymers

These are long chain structures obtained from smaller repeating units known as *monomers*. Polymers are formed by a process known as polymerisation. This is a process for converting monomers into giant organic chain structures by applying heat and/or chemical agents. Some of the common polymeric materials are high- and low- density polyethylene (HDPE and LDPE), rubber, nylon, polycarbonate (PC), poly vinyl chloride (PVC), and polystyrene (PS). Polymers typically exhibit good resistance to corrosion, low density and stiffness, poor conduction of electricity and heat, and a high coefficient of expansion on heating.

Composites

These are formed from the combination of two or more materials to achieve better properties than that of the original materials. Composites usually comprise a primary phase known as matrix and a secondary phase called filler/reinforcement material. Generally, composite materials are highly stiff, low in density, poor in thermal conductivity and high in fatigue resistance. It is to be noted that their properties can be manipulated based on the component materials to satisfy design requirements. Composite materials are used extensively in making reinforced concrete, brake materials, sports equipment, and the aerospace industries (Bello *et al.*, 2023).

Nanocomposites

The objects of reinforcements in composites can be micro or nanosized to enhance their effects on the sole or matrix material. Reinforcements with microscale materials have been reported to produce higher strength, elastic modulus, and hardness (Bello *et al.*, 2023). Therefore, nanoscale-reinforced metal matrix nanocomposites (MMNCs) that are reinforced with graphene, nanoparticles, nano fibres, and nanotubes exhibit strength properties that are superior to those of macro and microscale composites.

Semiconductors

Semiconductors constitute another important group of materials used in producing diodes, transistors, and light-emitting diodes. They exhibit electrical resistivity that lies between that of metals and insulators. Silicon and gallium arsenides are the two most widely used semiconductors. The electronic properties of silicon can be largely altered by deliberately introducing impurities such as boron, arsenic, and gallium into it.

Advanced materials

These are materials that are developed for high-technology applications. Advanced materials refer to nano-engineered and smart materials as well as some semiconductors and biomaterials. Examples are materials used for lasers, fibre optics systems, integrated circuits, information storage, liquid crystal displays, etc. Biomaterials are advanced materials which are compatible with the human body and are thus used to produce devices that functions to replace or regenerate body part or tissue or act to assist, augment or restore bodily functions. They are used to produce synthetic heart valves, sutures, artificial hips, hearing aids, dental implants, contact lenses, prosthetic legs, breast prosthesis and implantable blood glucose monitors. They can also be used for target drug delivery as in the treatment of cancer with gold nanoparticles. Biomaterials are safe for use in the human body and are resistant to corrosion. They also exhibit good strength and are durable.

Self-healing materials are smart materials that can repair themselves when damaged or broken. They are created by including polymers, nanomaterials, and catalysts into a material for use in some areas such as electronics, automotive, and aerospace. When damaged in service, the repair process that takes place by heat or pressure is set in motion by the substance embedded for the repair. For instance, in a “smart polymer” made of molecules that are designed to respond to an external stimulus, the molecules will get re-arranged and form a new molecule with a desired new shape to fill up any crack or gap and thus cause repair. A self-healing elastomer consists of two constituents, a healing agent, and a filler. When damage occurs, the healing agent reacts with the filler to form a polymer that can fill any crack or gap. In nanorobotics, when damage occurs, nanosized materials are triggered to begin the repair process (Frackiewicz, 2023).

Processing of Raw Materials

Raw materials are processed for the extraction of metals and non-metallic primary products which are further processed to obtain various engineering products.

Raw Materials

Raw materials are materials, solid, semi-solid, liquid, or gaseous which are naturally occurring on the earth and require processing by some techniques to obtain intermediate or finished products useful for mankind. A nation that is endowed with abundant raw materials has the potential to build a self-reliant economy based on industries that add value to its natural resources by appropriate technological processing. Primary raw materials can be categorised as either mineral, plant, or animal-based depending on their sources. Mineral-based resources include native metals like gold, industrial minerals like diamond and gypsum as well as metallic ores like galena for lead extraction and hematite for iron extraction. Examples of plant-based materials are cotton and rubber, while animal-based materials include animal skin. Engineering disciplines like agricultural, chemicals, food, and materials have the processing of these primary raw materials into products as the core of their operations.

Techniques for Metal extraction

Metals are mostly found in nature in combination with either oxygen, sulfur, or carbon dioxide depending on their varying degrees of affinity for the three to form oxides, sulphides, or carbonates in nature. In their stable combined forms, metals can be extracted from their ores by some techniques. However, the primary ores of the metals must be located by geologists through geological explorations such as airborne surveying. After locating the ore deposits, mining engineers must excavate the ore from the surface, sub-surface or underground using mining machinery and techniques. The run-of-mine minerals obtained are usually of grades that make them unsuitable for the direct processing of metals. In view of this, the primary ores must be subjected to some processing by physical and physico-chemical techniques of mineral processing to reduce their un-wanted gangue components and thus relatively increase the content of the mineral value bearing the metal of interest. Methods of mineral processing in use include gravity and magnetic susceptibility-based techniques like spiral and wet high-intensity magnetic separations, respectively. For instance, the grade of Itakpe iron ore as received is about 37% Fe, while the blast furnace smelting method proposed to produce liquid iron at the Ajaokuta Steel mill requires an iron ore concentrate with a minimum of about 63% Fe content for efficient smelting, while the Midrex based direct iron making at Aladja requires a super-concentrate with a minimum total Fe content of 66.7%. (Adeleke *et al.*, 2014).

Extraction of Iron

Liquid iron is mainly produced using the blast furnace. The blast furnace ironmaking process is a countercurrent process where hot gases rich in carbon monoxide-reducing gas is produced in the combustion zone as the hot oxygen blown through the tuyere rises in the bosh and encounters the charge (burden). The burden typically consists of sinters made from iron ore concentrate, limestone as the flux, and metallurgical coke as the reducing agent and source of heat for the smelting process. At the upper part of the furnace (stack) and a temperature below about 800°C, the higher iron oxides, Fe₂O₃ and Fe₃O₄ in the ore are reduced by C or CO to FeO. Afterward, part of the iron oxide produced undergoes indirect reduction to iron according to the Equation:

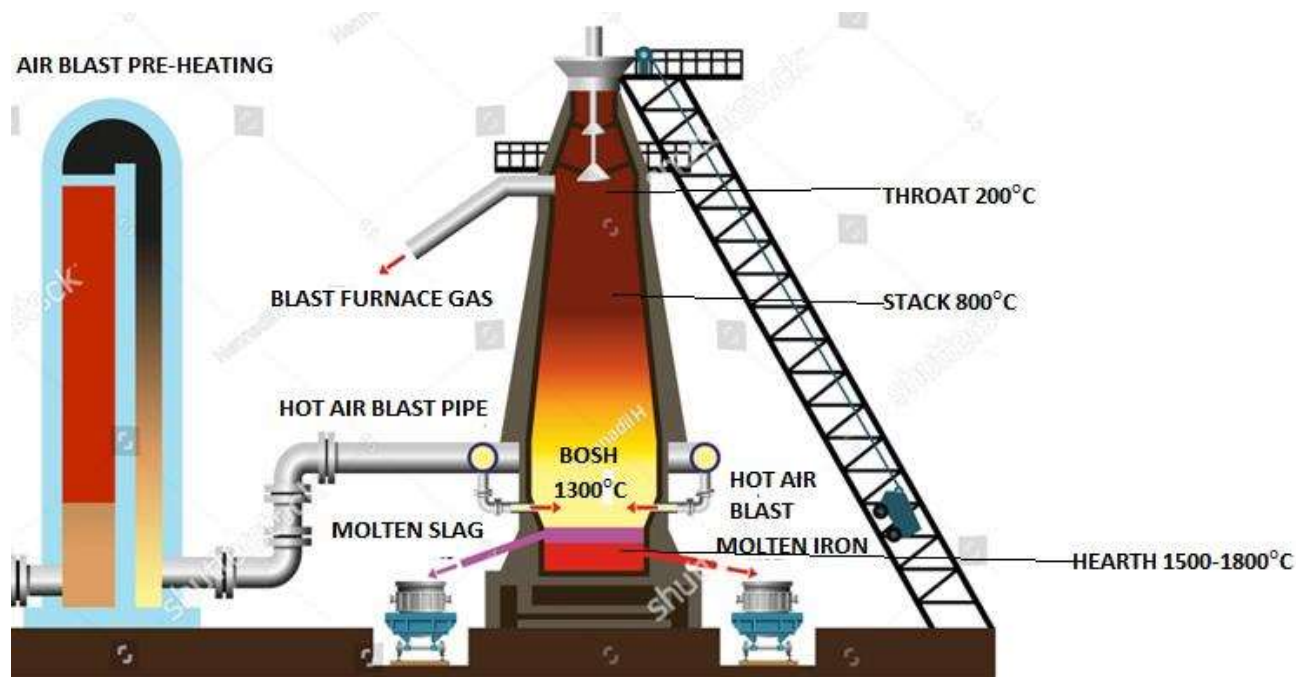


As the charge burden descends further down the shaft towards the bosh, it becomes hot enough to absorb between 3 to 4% C which reduced its melting point to about 1150°C. The FeO that remains also undergoes direct reduction by C as follows:



When the solid iron produced gets to the hearth region of the blast furnace where the temperature ranges between 1500 to 1800°C, it becomes molten. The high temperature of the hearth also led to the reduction of silicon (from silica) which dissolves in the molten iron. The limestone added to the burden get calcined to lime in the stack and combines with silica and other oxides to form a slag in the hearth. The slag formed floats on top of the molten iron in the hearth and the molten iron is tapped through a tap hole about four times daily.

The molten iron is delivered into the steelmaking vessels such as Bessemer Converter where air blast is directed into the hot molten iron having high carbon and high silicon to oxidise the carbon and silicon contents to the levels required for steel. Other steps like de-oxidation, de-sulphurisation, and de-phosphorisation are then carried out. The molten steel is cast into ingots for further processing. Figure 1 presents the schematic diagram of a modern blast furnace for



liquid ironmaking.

**Figure 185: Schematic diagram of a modern blast furnace (Shutterstock, 2023)
(Adapted)**

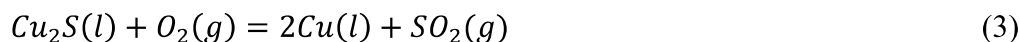
Apart from the blast furnace, solid direct reduced iron (DRI) is produced by processes such as the Midrex technology. The DRI produced is converted to liquid steel in an electric arc furnace (EAF) in an electric steelmaking process. In 2022, the blast furnace produced 1.28 billion tons of the world's output of liquid iron while the direct reduction/electric steelmaking route contributed only about 110.5 million tons; constituting 92.05 and 7.95%, respectively (GMK Centre, 2023). There are minimum strength specifications for coke to be used in the blast furnace ironmaking process (Adeleke *et al.*, 2006).

Extraction of Non-Ferrous Metals

Metals found as sulphides are extracted by first roasting the sulphide ores at a temperature below that of the metal or its sulphide. The roasted ore is then subjected to smelt. The sulphide ores of lead, zinc, copper, and nickel are treated by smelting to extract the metals. Reactive metals such as aluminium, magnesium, calcium, and alkali metals are extracted from their ores by electrochemical methods. For example, Al is extracted by fused salt electrolysis.

The copper sulphide (Cu_2S) ore flotation concentrate is roasted in a reverberatory furnace to finally produce a mixture of Cu_2S and FeS not reacted. The roasted ore is then mixed with

pulverised coke and silica to serve as reducing agents and flux, respectively for smelting in a blast furnace. The FeS is oxidised to FeO which reacts with silica to form iron silicate. At this temperature of the furnace, the less dense iron silicate slag, and a mixture of Cu₂S and unreacted FeS, called copper matte exist in a molten state. The matter, which contains 80 to 95% Cu₂S is taken into a converter where air is blown into it and the residue of Fe and FeS in it are converted to FeO. The addition of a silica-rich copper ore causes the fluxing of the FeO by iron silicate slag formation. The slag is removed, and more matte is added into the converter until it is almost full of matte. Air is then blown into the iron-free molten copper sulphide to produce the crude blister copper by the reaction:



The blister copper is further subjected to refining treatments by oxidation and electrolysis.

Techniques to Prevent Reverse Extraction - Corrosion

The natural tendency of metals is to exist in the atmosphere in a combined state as oxides, sulphides, and carbonates. The extraction processes are therefore carried out to produce pure metals against this natural tendency. However, under some favourable service conditions, metals tend to revert to their original combined stable states in a phenomenon called oxidation and corrosion. It has been reported by the World Corrosion Organisation (WCO) (2023) that the annual cost to the world from metal loss due to corrosion was US\$ 2.2 trillion as of 2020. The materials engineer uses the principles of corrosion science to design inhibitors and techniques to prevent or reduce this costly reverse of the extraction processes. Plate 1 shows four large, corroded pipes.



Figure 186: Picture showing corroded pipes (Corrosionpedia, 2023)

Preliminary Processing for Polymers and Ceramics

Plastics are said to be synthetic when the sources are natural gas, coal, and crude oil and bio-based when sourced from renewable materials such as combustible waste and biomass. The liquid/gas mixture obtained by heating a dense crude oil to boiling at about 600°C is taken into a distilling unit where the mixture is separated into light olefin gases like butane, ethylene, and propylene at <29.4°C and naphtha, a liquid mixture of hydrocarbons at 85 to 177°C. Naphtha is also produced from natural gas condensates and by distilling peat and coal tar. On heating, naphtha splits to form ethylene and propylene which serve as raw materials for plastic formation. The olefin gases serve as monomers to produce hydrocarbons of higher molar masses, called polymers during addition and condensation polymerisations.

Most ceramics are produced from kaolin and ball clays. The clay slurries, single or a mixture of different clays are blended with feldspar and quartz. Feldspar, a flux, produces a glass phase that cements other crystals in the clay mixture and thus improves strength and toughness. It also provides the alumina and alkalis required for the subsequent glazing process. Quartz in its unchanged form serves as an embedded aggregate that increases thermal expansion and eases the placement of glazes on the ceramic product.

Materials Processing Techniques

The techniques to process metallic and non-metallic materials to various products after their extraction and primary processing are outlined as follows:

Processing of Metals

Metal fabrication processes refer to the techniques by which metals are shaped, formed, and treated to obtain desired products. The techniques include casting, rolling, and forging. In forging, a compression force is used to obtain a desired shape. When carried out manually, a blacksmith heats a metal to the point that it can be hammered to bend and form desired shapes. In casting, a metal or its alloy is melted and made to flow into a mould where it solidifies. Casting is the preferred process for mass production since the mould can be used repeatedly with minimal variation in the product. They are also used to produce intricate shapes and large-sized products like machine tool beds. Plate 2 shows typical cast products.



Figure 187: Typical cast products (EPD, 2023)

In metal drawing, a tensile force is used to pull a metal through a tapered die and thus causing it to stretch into a thinner shape. It is most used in sheet metal fabrication to obtain box-like or

cylindrical-shaped final products. In forming, a metal is bent to the angle desired using a brake press that applies pressure to the metal. Machining is a subtractive shaping process that creates a new form by removing unwanted material. The technique may involve drilling, turning, shaping, and milling using drilling, lathe, shaping, and milling machines, respectively. A Computer Numerical Control (CNC) machine is the modern most common tool used for turning and milling. It processes a workpiece to specifications based on numerical control principles using coded programmed instructions and without the control of a manual operator.

During extrusion, a metal enters an opened or a closed die by force and thus making it assume the cross-section of the die as it gets reduced. The end product is usually cylindrical. In cutting, large pieces of metals are cut into smaller ones using a hacksaw and modern equipment like lasers, waterjets, power scissors, and plasma. In punching, punching presses carrying special-purpose turrets produce holes in a workpiece at desired locations. Stamping is similar to punching, but it has to do with producing indentations like letters, shapes and images on a metal using a press or a hammer. Welding is the art of joining two or more pieces of metal of different shapes and sizes through a combination of heat and pressure. Welding techniques commonly used include metal inert gas (MIG), tungsten inert gas (TIG) and flux-cored arc (Metal Fab, 2023).

Processing of Polymers

Polymeric materials are processed into desired products by extrusion, injection moulding, thermoforming, and rotational moulding. Extrusion is the most important technique to process thermoplastics. Granules of the polymer are delivered into the screw extruder through the hopper while heat is supplied externally and through the barrel into the granules. The screw draws in the polymer granules while maintaining friction with the barrel wall. This causes the granules to be heated, mixed, homogenized, and melted. The molten and compacted polymer then leaves the extruder through a shaped die that has a geometry that determines the shape of the product, such as sheet, pipe, rod, or channel. Figure 2 shows the schematic diagram of a screw extruder.

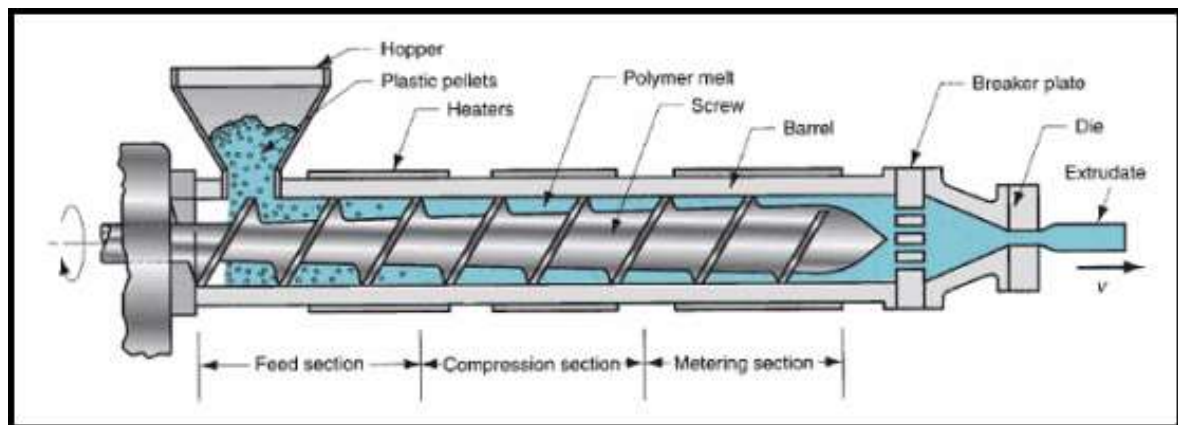


Figure 188: A screw extruder machine (SUKO, 2023)

In injection moulding, a molten polymer is forced at high speed and pressure into a shaped mould where it cools rapidly and takes the desired shape. Waste polymer in the form of sprues is removed from the product. Thermoforming is used to produce large plastic parts in simple shapes. The plastic sheet is heated, and it softens and then deforms under vacuum suction or pressure. In rotational moulding, a hollow mould is charged with polymer and then subjected to heating and rotation. It is afterwards subjected to final cooling and rotation to form the desired product.

Processing of Ceramics

Traditional ceramic processing involves the use of clay to produce bricks, porcelain and potteries on a potter's wheel, Advanced ceramics processing uses carbides such as those of silicon and tungsten to produce ceramic products for body armour and applications in aerospace and medicine. In injection moulding, the ceramic material is heated to melt and then forced into a mould of the desired shape. In dry pressing, ceramic powders are compressed into a die of the desired shape and then heated for tempering. The product may be glazed by spraying to enhance some physical properties of the part. The final product is sintered at 1000 to 1200°C to harden it and increase its density. In slip casting, a slurry of clay is delivered into a plaster mould for forming and hardening into a product of very precise and consistent shape. Advanced ceramics include O-sialons that exhibit excellent thermal shock resistance and boron carbide (B_4C) that provides extreme hardness for body armour production.

Emerging Technologies for Material Processing

There are several novel techniques for processing materials to impart superior mechanical, electrical, magnetic, and optical properties desired for specific applications. These techniques include the following:

Additive Manufacturing

In additive manufacturing (AM), products are made by building them one layer after another. It is the opposite of subtractive production used in machining where a product is made by cutting from an original larger-sized blank. The process involves the design of the product using computer-aided design (CAD) software and the interpretation of the design by software into a layer-by-layer framework for an additive manufacturing machine to implement. AM can be implemented with metals, polymers, ceramics, foams, gels, and biomaterials. The advantages of additive manufacturing include the possibility of producing a single object rapidly since a design can be sent to a 3D printer directly from a computer. AM also enables the production of objects with materials that are selected to perform some intended functions. For instance, it is possible to produce a product with a wear resistant ceramic surface and an electrically conductive metal core.

Nanotechnology Techniques

Nanotechnology deals with the synthesis of nanosized materials such as nanoparticles, nanotubes, nano fibres, coatings, dispersions, and nanocomposites. Nanoparticles have diameters between 1 and 100 nm and can be made from carbon, ceramic, metal, semiconductor, and polymer. Nanofibres are nanostructures in a cylindrical shape having an outer diameter of less than 1000 nm and an aspect ratio higher than 50. Nanotubes are nanoscale hollow tubes with aspect ratios greater than 1000. Nanoscale structures exhibit highly improved physical and mechanical properties because as the size of particles in each mass of material decreases, the surface area increases leading to a decrease in melting point, and improved magnetic and optical properties, among others. Nanoparticles are used to obtain enhanced reaction catalysis and as a coating for ultraviolet ray protection.

Nanoparticles are synthesized by the bottom-up approach that assembles single atoms into larger structures using methods such as spark ablation and colloidal chemistry. In the top-down approach such as ball milling and mechanical alloying, macroscale particles are intensely ball milled to nanosizes and blended with metal powders to produce products such as oxide-dispersion strengthened (ODS) nickel and iron-based superalloys for aerospace applications (Nanoscience Instruments, 2023).

The advanced products of nanotechnology are used in aircraft, spacecraft, rockets, fibre optics, and computer systems. Special equipment used in nanofabrication includes ellipsometer, reflectometer, and atomic force microscope.

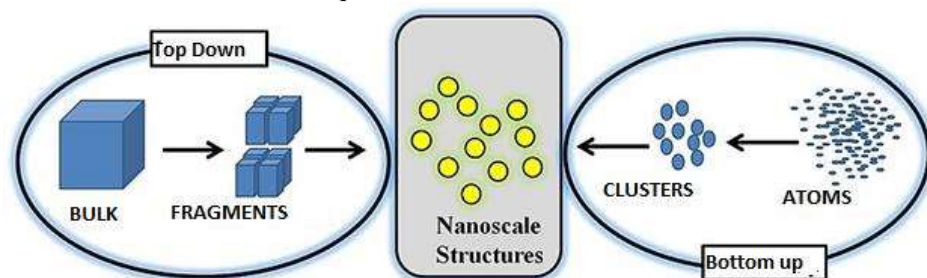


Figure 189: The emerging techniques of nano-processing (Nanoscience Instruments, 2023)

Thermomechanical Processing

There are three rolling methods, namely, conventional, normalising, and thermomechanical rolling starting with a slab having a relatively coarse grains microstructure. Thermomechanical rolling is carried out in two rolling sequences at a temperature lower than normalising rolling leading to a finer-grained microstructure of the slab. The slab workpiece is made to shift back and forth on the roller table until the final forming temperature of between 800 and 900°C, where the slab ceases to recrystallise is attained. After austenitisation, the slab is rapidly cooled to temperatures below 600°C causing the formation of an extremely fine-grained substructure with high strength, very good toughness, and better weldability than normalised steels. Thermomechanically (TM) rolled steels exhibit high yield strength that ranges between 275 and 460 MPa. They are used to construct welded structures like bridges that work under high-stress service conditions.

Metal Finishing Processes

Metal finishing can be of either adding/altering or removing/re-shaping type. In the former, the layer of a material that will provide the properties such as strength, conductivity, aesthetics, durability, and corrosion resistance desired is deposited on the product. The techniques that are commonly used to add/alter include galvanising, powder coating, passivation, electro and electroless plating. In hot deep galvanising, an iron or steel part is inserted in molten zinc to obtain a zinc coating on it. In electroplating also known as electrochemical deposition, a cleaned substrate component made from a material that is relatively cheaper and lower in density such as steel is encapsulated with one or more expensive and denser materials such as gold, copper, zinc, and nickel in an electrolytic cell. The solid substrate serves as a cathode where a reduction reaction to deposit another metal takes place. In electroless plating, the deposition of metals on a solid substrate takes place in a reducing chemical bath and not electrolytically. In powder coating, a mixture of additives like pigment and curatives are electrostatically deposited on the solid substrate and heated in a special oven to produce long-chain, cross-linked molecules. Figure 4 shows the electroplating process.

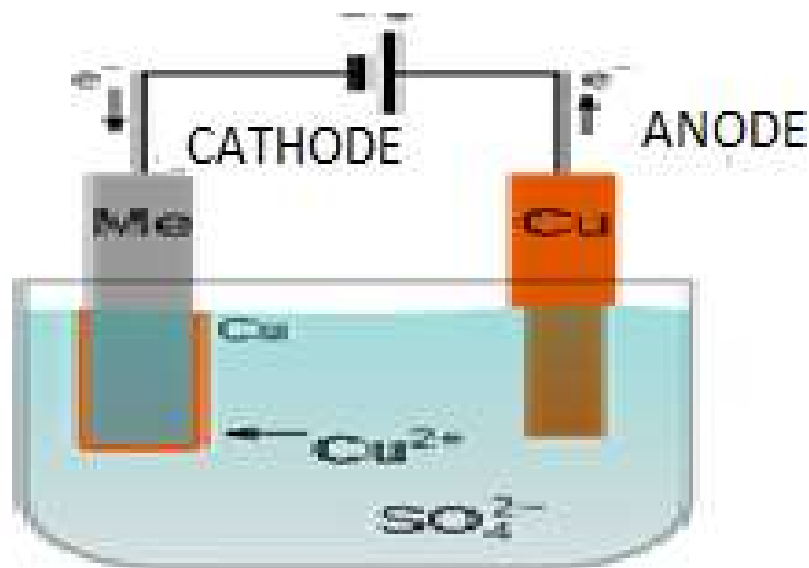


Figure 190: Electroplating of Cu on metal (Me) (Torsten, 2006)

In the removing and re-shaping finishing, the surface of a part is altered by removing material from it or re-shaping it to achieve the client's desire for aesthetics, polish, or re-shaped part. Techniques in common use for removing and re-shaping include electropolishing, abrasive blasting, and buff polishing. In electropolishing, electric current is used to remove cations from the surface of a component made from an alloy like stainless steel to eliminate peak and valley defects.

Selection of Engineering Materials

The selection of appropriate materials is one of the most important tasks in engineering production. For a specific application, a materials engineer must be able to choose the right and appropriate material with the best blend of properties. The factors that affect materials selection for any engineering application include properties of the material, fabrication requirements, dimensional tolerance of the material, service requirement (mechanical properties, electrical and thermal properties, corrosion resistance, physical properties, etc.), and cost and availability of material.

The procedure of Materials Selection

The selection of suitable material for an engineering application is expected to meet certain standards. These include the performance of the materials, their reliability, degradability, manufacturability, and recyclability. Figure 5 presents a sequence of activities needed to engineer a structure or component.

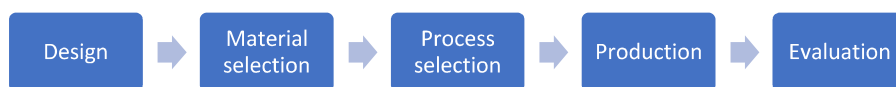


Figure 191: Flowchart of a sequence of activities an item undergoes.

There are four basic steps involved in the selection of materials, these are:

- i. identification of the design requirements.
- ii. identification of criteria for the selection of materials.
- iii. identification of the candidate materials.
- iv. evaluation of the candidate materials and finally
- v. selection of materials.

Materials Properties Classification

Material properties can be classified as the mechanical, physical, or chemical behavior of a specific item that would determine its functionality and processing. These properties are mechanical, electrical, thermal, magnetic, optical, and deteriorative.

Mechanical Properties of Materials

These are useful to evaluate how a material will respond to mechanical loads applied to it. It provides information on when a material will fail under different mechanical loading

conditions. These loading conditions could be compression, tension, torsion, bending, cyclic, impact, etc. Examples of mechanical properties of materials are tensile strength, compressive strength, yield strength, fracture toughness, elastic modulus, ductility, hardness, etc.

Electrical Properties of Materials

These properties provide information about the ability of a material to transmit electric current. It is referred to as conductivity and resistivity. Based on the electrical properties of material, they can be classified as conductors, semiconductors, or insulators. Typically, metals are good electrical conductors while ceramics and polymers are known as insulators due to their very low conductivities. However, there are some materials with intermediate conductivities. These are known as semiconductors.

Thermal Properties of Materials

The thermal property of a material refers to its response to heat. The application of heat to a material will cause an increase in temperature and dimension. The heat may be transferred from one region of the material to another and ultimately, the material will melt. The properties of the materials that are associated with heat application are heat capacity, thermal conductivity, thermal expansion, and thermal stress.

Magnetic Properties of Materials

These are properties exhibited by materials that determine their attractive or repulsive interactions with other materials. Generally, materials that can attract a magnet are known as magnetic materials (e.g. iron, cobalt, nickel, etc.) while those that cannot be attracted to a magnet are known as non-magnetic materials (e.g., aluminium, copper, wood, etc.). Based on the strength of interaction with a magnet, materials can be classified as diamagnetic, paramagnetic, ferromagnetic, and anti-ferromagnetic where the material is weakly repelled by magnetic fields, weakly attracted by magnetic fields, strongly attracted by the magnetic field, and can be magnetized permanently respectively.

Optical properties of materials

This property is based on the interaction of a material with electromagnetic radiation. One of the examples of electromagnetic radiation is visible light which consists of particles known as photons. The interaction of photons with a material determines its optical properties. Absorption of light occurs when photons give their energy to the material while reflection occurs when photons of identical energy are emitted by the material. When photons are unable to interact with the material, it is known as transmission. Based on interaction with visible light, materials are classified as transparent (can transmit light with very little absorption and reflection), translucent (can transmit light partially), and opaque (resistant to the transmission of visible light).

Deteriorative Properties of Materials

Deterioration is the loss in the properties of a material by chemical interaction with the environment or heat. In metals, there may be material loss either by *corrosion* or *oxidation*. Compared to other classes of materials, ceramics have higher resistance to deterioration. For polymers, the mechanism for deterioration is different from those for metals and ceramics. Deterioration of polymer may occur when it is dissolved in a liquid solvent, or on exposure to

heat/electromagnetic radiation. In summary, the properties of materials are identified based on the stimulus imposed on them and the subsequent responses generated.

This is presented in the table below:

Table 25: Properties of materials and the appropriate stimuli

Properties	Stimulus imposed	Responses generated
Mechanical properties	Mechanical load	Deformation/Rigid body motion
Electrical properties	Electric field	Conduction/Insulation
Magnetic properties	Magnetic field	Magnetization
Thermal properties	Heat	Conduction
Optical properties	Visible light	Reflection/Absorption
Deterioration	Chemicals	Corrosion

Laboratory Procedures for the Investigation of Materials Structures and Properties

The science of materials is centered on studying the relationships between structures and properties. This provides the opportunity to design materials with predetermined properties for an intended engineering application. To study the structure of a material, preparation of a specimen surface for microscopic examination is done followed by examination of the surface characteristics.

Specimen Preparation

The preparation of specimens for metallurgical operations is essential for the characterisation of materials. These operations are in stages and presented below:

Sectioning: This operation involves the removal of a small portion of the specimen from the big piece. This process is done carefully to avoid any possible alteration to the microstructure of the material. This can be achieved by cutting with the aid of a bonded abrasive wheel. Coolant is also applied during the cutting to reduce heat and possible deformation of the materials during sectioning.

Mounting: For easy handling of the specimen and protection during subsequent metallurgical operations, it is essential to mount the specimens appropriately. The frequently used methods are Compression and Cold mounting. Compression mounting is achieved by placing the specimen in a cylindrical-shaped polymer with the application of pressure at elevated temperature with the aid of a molding machine. On the other hand, cold mounting is done by

positioning the specimen at the center of a metallic ring containing liquid mounting material and placed on a glass plate. The mounting material is gradually poured into the ring until the specimen is covered. Some frequently used mounting materials are polyesters, epoxides, acrylics, etc.

Grinding/Polishing: These processes are achieved by consecutive grinding (from coarse and medium grinding to final polishing). The specimen is initially rinsed before progressing from one operation to the other. Coarse grinding is done to obtain a flat surface while medium grinding is obtained by grinding continuously using finer grits of grinding paper. The polishing is done to completely remove coarser scratches from the previous grit. This can be achieved using a rotating wheel covered with fine abrasive particles (alumina). During polishing, drops of water are continuously added to the rotating wheel to obtain a well-polished specimen.

Etching: The result of this properly ground and well-polished specimen is a smooth surface. This surface will usually deflect any incident lights from a metallurgical microscope which makes it difficult to obtain the surface characteristics of the specimen. Etching is done to reveal these surface characteristics. It is defined as the process of using an acid or any chemical solution to attack the surface of the specimen to reveal structural information on it.

After the surface of the specimen has been well prepared, the operation is followed by an investigation of the surface characteristics. This is achieved with the use of techniques that require magnification of the surface of the material. Optical microscopes, electron microscopes (Scanning Electron Microscope and Transmission Electron Microscope), and other scanning devices are used for the general-purpose characterisation of materials.

Heat Treatment Equipment and Procedures

Heat treatment processes are operations that involve heating and subsequent cooling of a metal or an alloy to obtain desired properties while the composition of the material remains unchanged. Heat treatment is done to change or modify the microstructure of the material. It is carried out to improve the properties (mechanical, electrical, thermal, magnetic, wear resistance, corrosion resistance, etc.) and machinability of materials. The process of heat treatment involves heating the metal above its critical temperature, held at that temperature for a particular time, and finally cooling in a medium (water, air, or molten salts). The different types of heat treatment processes are presented below:

Annealing: This is the most used heat treatment operation in the processing of iron and steel. It requires heating of the metal from 30 – 50°C above its critical temperature and then cooling inside the furnace at a slow rate. This process will increase the ductility and malleability of the metal. It also makes steel soft for easy machining.

Normalising: This process is carried out to return the structure of a metal or alloy to normal. It is necessary to remove any internal stress resulting from cold working. During normalising, steel is heated to about 30 – 50°C above its upper critical temperature and then cooled in the air. It improves the mechanical and electrical properties as well as the machinability of a metal.

Hardening: This heat treatment process involves heating the metal to about 30 – 40°C above the upper critical temperature and then cooling rapidly to room temperature in water or oil. It is the opposite of annealing. This process is carried out to make steel hard. It improves the resistance to wear (hardness) of metals.

Tempering: After the hardening process of a metal specimen is completed, it becomes brittle. To reduce this brittleness caused during hardening, the process is followed by tempering. This is necessary to increase the product's usefulness. During tempering, the quenched metal is

reheated in a bath of oil or molten salt to a temperature marginally above the temperature range at which it is to be used. It is then held in the bath until the temperature becomes even. Finally, the specimen is removed from the bath to cool in the air. Tempering is done to enhance the ductility and toughness of the metal.

Nitriding: This is another process of surface hardening which requires nitrogen gas to obtain a hard surface for a metal. In this process, nitrogen atoms are deposited on the surface of the metal when it is heated in the presence of ammonia. Nitriding is carried out in an electric furnace at temperatures between 450 and 510°C. This process increases the hardness of the metal surface and improves its resistance to wear, corrosion, and fatigue.

Cyaniding: This process involves heating steel in sodium cyanide which results in the deposition of carbon and nitrogen atoms on its surface. During cyaniding, the metal specimen is immersed in a molten cyanide salt bath at a temperature of about 950°C and left in it for about 15 to 20 minutes. The sodium cyanide produces nitrogen and carbon, which are diffused into the surface of the metal. The specimen is then taken out of the bath and rapidly cooled in water or oil. This heat treatment process is very effective for enhancing the fatigue limit of metals. However, this process is now being discouraged because of the health hazard associated with cyanide.

Carburising: This process involves heat treatment of a metal specimen in the presence of carbon. Carbon atoms are deposited on the surface of the metal during carburising. Similar carburisation can be performed in the laboratory by using the Boudouard reaction with the adjustment of carbon monoxide-carbon dioxide atmospheres according to the Equation: (Rudnev and Totten, 2014)



Case Hardening: This heat treatment process is carried out to increase the hardness of only the surface of the metal while the core remains soft. It is simply a carburisation or other heat treatment process by which only the surface is hardened while the core remains soft. Case hardening is done to obtain a metal with a hard surface and a tough core.

Summary

In summary, materials engineering deals with the extraction of metals and the development of ceramics, polymers, and composites from their raw materials using the principles of basic science, metallurgy, and materials science. It involves continuing research using the principles of thermodynamics, alloy design, heat treatment, and nanoscience to improve the properties of existing materials and to synthesise more advanced materials for use in making advanced engineering products like computer chips, biocompatible devices, and aircraft wings. The materials engineer has the expertise to select appropriate materials for specific applications and to design techniques and inhibitors to prevent or reduce the occurrence of reverse extraction in metals and metallic alloys, called corrosion. A graduate of materials engineering can be employed as an engineer-materials, mineral processing, corrosion, quality control, research, design; scientist-metallurgist, research officer, etc.

Recommended Visual Learning Aids

1. The blast furnace ironmaking process

(<https://www.youtube.com/watch?v=8s8rcnxqLIw>, Accessed 10th April, 2023)

2. Thermomechanical rolling

- (<https://www.youtube.com/watch?v=0RZGINVGgig>, Accessed 10th April, 2023)
3. Bayer process for Al extraction
(https://www.youtube.com/watch?v=-Fu_KIOGVQ4, Accessed 11th April, 2023)
 4. 3D printing material jetting
(<https://www.youtube.com/watch?v=oi0JEhGqTuU>, Accessed 10th April, 2023)
 5. Animation for nanotechnology
(<https://www.youtube.com/watch?v=1QwyMWM0Jjg>, Accessed 10th April, 2023)

Exercises

1. Explain the distinguishing roles of materials engineering in material processing.
2. “Materials engineering is a specialisation in materials science and engineering”. Discuss
3. Enumerate the four categories of materials and briefly describe each group.
4. Distinguish between the blast furnace iron making and the direct reduced iron (DRI) techniques of steelmaking.
5. Describe the principles and practice of emerging material processing techniques such as thermomechanical rolling, material jetting, and sol gel bottom-up synthesis.
6. Outline the procedure for materials selection.
7. Explain why heat treatment is an essential procedure in material processing.

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Biodata of Authors



BIODATA of Professor Abraham Adewale Adeleke

Abraham Adewale ADELEKE is a Professor in the Department of Materials Science and Engineering, Obafemi Awolowo University, Ile Ife (2015-Date,) and Head of the Department (2018-2021) which he joined in 2006. He was a Chief Metallurgical Engineer (2001-2006), at the National Metallurgical Development Centre (NMDC), Jos. He is the current University Director, Industrial Training Coordinating Unit (ITCU/SIWES). He has over 40 article's in reputable journals and Conference proceedings such as the 2020 Minerals, Metals and Materials Society's (TMS) Confet San Diego, USA. He is the author of a book titled Mineral Processing Technology-A concise introduction by Taylor & Francis (2023)



BIODATA of Dr Kabiru MUSTAPHA

Associate Professor, in Kwara State University with Ph.D., Materials Science & Engineering, African University of Science and Technology, Abuja (2015), Master of Science, Material Science, African University of Science and Technology, Abuja. (2010), Bachelor of Science (Hons) Physics (Second class upper division), Ahmadu Bello University, Zaria. (2009)



BIODATA for Professor AbdulGaniyu Funsho ALABI

AbdulGaniyu Funsho ALABI, Professor in the Department of Material Science and Engineering, Kwara State University, Malete. He attended University of Pittsburgh, Pittsburgh, P.A., U.S.A., (1983-1988), Imperial College of Science & Technology, London, (1977-1978), University of Ife, Ile Ife, (1971-1974). He holds a Ph.D. in Metallurgy & Materials Engineering, M.Sc. / DIC. (Engineering) in Extractive Metallurgy and B.Sc. (Hons.) in Chemistry