INAUGURAL LECTURE SERIES 289

ENGINEERING MATERIALS-PRIME MOVERS OF GLOBAL TECHNOLOGICAL DEVELOPMENT AND INNOVATION

By

Benjamin Iyalekhuosa IMASOGIE

Professor of Materials Science and Engineering

OBAFEM LOWO UNIVERSITY PRESS, ILE-IFE, NIGER

BENJAMIN IYALEKHUOSA IMASOGIE

Professor of Materials Science and Engineering

ENGINEERING MATERIALS – PRIME MOVERS OF GLOBAL TECHNOLOGICAL DEVELOPMENT AND INNOVATION

An Inaugural Lecture Delivered at Oduduwa Hall,
ObafemiAwolowo University, Ile-Ife, Nigeria,
On Tuesday 23rd August, 2016

By

Benjamin IyalekhuosaIMASOGIE
Professor of Materials Science and Engineering

Inaugural Lecture Series 289

ObafemiAwolowo University Press Limited,
Ile-Ife, Nigeria.

ISSN 0189-7848

Printed by

ObafemiAwolowo University Press Limited
Ile-Ife, Nigeria.

1. Introduction

Mr. Vice-Chancellor Sir, my distinguished audience, it is with immense gratitude to the Almighty and All-knowing God and indeed a great privilege that I stand before you today to deliver the 289th Inaugural Lecture of the Obafemi Awolowo University, Ile-Ife. It is the second inaugural lecture to be delivered from the Department of Materials Science and Engineering and arguably by the first indigenous Ph.D holder in materials engineering in Nigeria. The first inaugural lecture titled "Materials, Energy and the Environment" was delivered a little over three (3) decades ago by my mentor, Ph.D supervisor and the first indigenous resident Professor of Metallurgical and Materials Engineering in Nigeria; Prof. A. A. Afonja (we call him **'triple As**!). There is no doubt that much of his academic philosophy has been adopted as my own and that he will indeed find many an echo of his own lectures in these pages.

Technology has been described as the main propellant of human development. The level of this development has been the basis for characterizing nations of the world as developed, developing (or even underdeveloped, if we have to be frank with ourselves here!). Generally, the major development indicators are; Healthcare, Social Amenities, Education, Communication, Transportation, Energy/Power, Gross-Domestic-Product (GDP), Gross National Product (GNP), etc. Innovation on the other hand alludes to a new, unique, outstanding thing or a modern, remarkable and/or original method, idea, style, breakthrough or process of doing something. Materials, energy and the environment are closely interrelated. In fact, human development is defined by the World Bank as a sustainable increase in living standards that encompass material consumption, energy, education, health and environmental protection. Materials are basic to manufacturing and service technologies, to national security and to national and international economies. It is however clear that a civilization is both developed and limited by the materials at its disposal and this has been evident from time immemorial. Thus, the technological development level of a country is usually measured with reference to its innovations, patented products and high-quality certified materials production (Briggs, 1995). Indeed, the pattern of consumption of engineering materials has become a strong indicator of the level of development of modern civilization. According to Ashley and Greenemeier (2013), the future of manufacturing depends on a number of technological breakthroughs in robotics, sensors and high performance computing, to name a few. But nothing will impact how things are made, and what they are capable of, more than the materials that manufacturers use to make those things. New materials change both the manufacturing process and the end result/product. Fleming and Cahn (2000) further stressed that recent advances in materials R & D are linked to future prosperity of developed nations and are major driving forces for global economic growth.

It is therefore the thesis of this inaugural lecture that virtually every old or modern technological development and/or innovation depends primarily on the design and availability of the appropriate engineering materials. Thus if technology moves and sustains the World, then materials development must be the major driving spirit! The world of engineering materials has become the core or crucial arena for global technological development and breakthroughs. Materials Science and Engineering has been identified as an intellectually exciting field, crucial to the success of national industries, economic welfare and defense (National Research Council, (1989)).

Let me make this assertion from the onset of this lecture and for which I am in total agreement with my mentor; Prof. A. A. Afonja, that indeed, man's greatest achievements in the last century or thereabouts, are not necessarily development of the steam engine, nuclear power, the turbo-jet engine, the computer, laser and maser, the artificial human body parts/implants, achievements in space exploration, internet or even the advent of smart phones, iPods, iPads, etc, but rather the ability to produce the requisite materials on which these feats depended (Afonja, 2002). Today, there are metal-based materials and composites that can withstand ultra-high temperatures and radioactive environments of nuclear power and allied reactors, the appropriate gear and equipment/kits for astronauts, heat-resistant ceramic tiles and unit lining components to enable their space shuttle to re-enter the earth's atmosphere without burning up, specially engineered materials with fantastic strength-to-weight-ratios fit for modern athletics/sporting gears/kits and vehicles, large-bodied commercial aerodynamic jetliners and stealth warplanes, semiconductors and multi-chips for sophisticated computer circuits and telecommunications equipment, trans- and intercontinental optical fibre cabling, 'smart' materials-sensors and actuators, satellite systems, etc., all examples of material systems which provided the key to viable designs of the aforementioned developments and breakthroughs. Thus, without them, some of our greatest achievements, innovations and outstanding systems, tools, devices, appliances, robots, etc., would not have been possible now or even sometime in the very distant future. What is also clear is that most of these successful and competitive system and product designs could only have been transformed into useful products and innovations because of the development and availability of the requisite, optimal materials and technologies. Likewise, the development of most of the latest inventions in nanotechnology such as paper-like displays, digital mirror display (DMD), nanoswitches, gears, sensors and accelerometers (for the deployments of Airbags), nano-transducers and machines, inkjet nozzles and 3-D printers, vision "smart dust" and walking microrobots used in military intelligence work, etc., that we are celebrating today, depended to a large extent on development and availability of the required nano-structured and allied materials.

Materials science and engineering is a multidisciplinary training, research and development field that is concerned with the generation and application of knowledge relating the composition, structure and processing of materials to their properties and applications. Practitioners in the field develop and work with materials that are used to make functional products like machines, devices and structures. The multidisciplinary nature of materials science and engineering is evident in the educational background of majority of scientists and engineers all over the world, who, in varying degrees, are working in the field. The fact is that many technological advances and development in other fields of engineering are closely related with progress in materials R & D; which has the potential to trigger a sustainable technological boom, as witnessed in the last couple of decades in Asia and the, Far East, where materials professionals have sought to understand the subject for improved engineering practice and competence.

The vital role of materials science and engineering particularly as it relates to successes in some of the active fronts of technological development in other engineering fields, be it in transportation, building, road and rail construction, military weaponry and defense-armory, communication, oil and gas, computer hardware architecture, electronics, telecommunications and information technology, mechatronics, etc., or even in the proliferation of surgical material implantation practice, dentistry, tissue engineering, etc., has always been materials driven. Therefore, it can be said that every other scientist or engineer depends heavily on the materials scientist and engineer in order to function fully in today's world. Thus moving forward, it is my honest opinion that all science and engineering disciplines need to know much more about materials. Recent advances in materials R & D, design, modeling and manufacturing have opened up new vistas and frontiers that are effectively moving product and component designs down to mainly materials design issues! Today, it may surprise some of us that there are engineered plastics stronger than steel, near zero friction from nanoscale lubricants and engineered materials harder and brighter than diamond!

Mr. Vice-Chancellor sir, in this lecture, the materials-technology-human development interface is critically examined with particular emphasis on the prime role of engineering materials in technological development and innovation. The efforts of researchers, institutions, governmental and non-governmental materials' policy initiators and funding agencies in a series of R & D breakthroughs in novel materials and niche areas of their applications are highlighted. The Nigerian experience in engineering materials development will be critically appraised. Some current developments in materials science and engineering will be examined and the contributions emanating from teaching and research activities of materials professionals at Obafemi Awolowo University, Ile-Ife, in particular, highlighted.

2. It is a Materials' World!

Materials are a defining characteristic of society. It is a well known fact that Materials have played a very critical role in the existence, development and survival of mankind. From pre-historic times, man has been heavily dependent on materials for tools, clothing, shelter, hunting, agriculture, transportation, recreation and military weaponry. In fact until very recently, notable materials have been used by historians to define or label the various civilizations based on the recognizable material in dominant use for these human endeavors during the periods. Thus we have the 'Stone Age' (about 10,000 years ago), the 'Bronze Age' (1,500 B.C.), the 'Iron Age' (1000 B.C.) and the 'Steel Age' (~1700 AD), as shown in Figure 1 (Tsipas and Olmos (2016)). However, this classification mode have been found not to be fitting enough or adequate for various reasons. Modern carbon dating methods have shown clearly that the origin of materials is traceable to about 20 billion years ago when the earth was created (Britannica Online Encyclopedia, 2015). Also, archeological history records and recent carbon dating on excavation findings have shown evidence that the early man was already quite familiar with fundamental and powerful concepts of metallurgy and materials engineering such as ore smelting, winning, refining and alloying as far back as 2000 B.C.

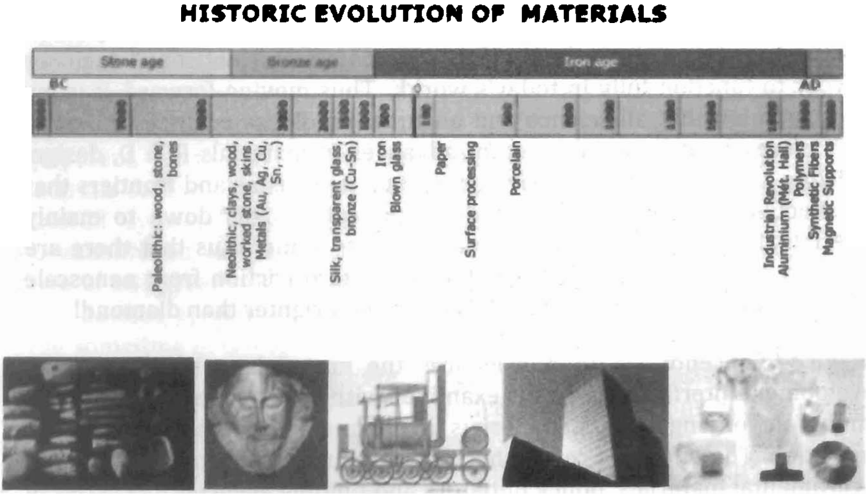


Figure 1: Artifacts of Civilization: (Tsipas and Olmos (2016). www.uc3m.es: Chapter_1_1.pdf)

Other minerals/materials such as copper, gold, silver, bronze, brass, etc., were being mined, smelted, processed, refined and polished in different periods well before or that which transcended the aforementioned ages. There is ample evidence that meteorites were used as a source of iron before 3000 BC, although extraction of the metal from ores dates from about 2000 BC (Britannica Online Encyclopedia, 2015).

Roman history also records that man learnt to make fires hot enough to melt mineral ores and metals in earthenware containers; called 'crucibuli' (known today as the 'crucible'), well before 1000 B.C. He discovered early 'metal casting', 'heat treatment' and 'metal-working' and 'blending' (alloying today) methods and principles during this early period. As it would be expected, it was during this period that major nations became clearly aware of their military superiority and/or limitations after a series of seemingly un-ending wars of attrition and subjugation. Thus, the nations that knew their 'materials' and/or had the better-material weapons and amours did 'exploits' in those wars and became military 'super-powers' in those days.

Today, classification of civilization seemed to have shifted from the dominant material in use during the aforementioned time ranges, to the more appropriate 'material-product' format. We now talk about the 'Locomotive Age', 'X-ray/Holography Age', 'Atomic-'Bomb'/Nuclear Age', 'Telephone Age', 'TNT/Dynamite' Age, 'Semi-Conductor (or Transistor/IC/Electronic) Age', 'Radio/Television Age', 'Computer Age', 'Jet (or Turbo-Engine) -Age', 'Super-sonic Age', 'Rocket Age', 'Super-conductor Age', 'Robotic Age', 'Space Age', 'Laser Age', 'Cable Network/Internet' Age, 'Hybrid/Polymer/ Ceramic/Composite Materials Age', 'Smart-Materials' (Graphene-Carbon Nano-Tube) Age, 'Exotic Materials Age', '3-D-Printing/Materials' Age, etc. Again, it has been observed that the time frames associated with these material-based developments seem to always overlap a lot and/or tend to spread over rather short but same time-frames, such that a lot of arguments of classification still persist. It is however safe to call this present age as the 'Advanced Materials Age'!

Thus from the humble beginnings of the early man who had access to only a very limited number of materials, particularly those that occur naturally; stone, wood, clay, hides and skin, etc, to the medieval man who developed techniques for producing materials (pottery, clay and glass-wares, porcelain/china-wares, ferrous and non-ferrous metals, etc.) with superior properties to those of the natural ones, it has been a heavy dependence on materials for his well-being, such that virtually every aspect of his everyday life was influenced to one degree or another by his materials. While the Stone Age man was quite proficient in flaking flint into knives, hand axes, spearheads, etc., by hammering with selected stones, the medieval man also discovered that the service properties of a material could be altered by heat-treatment, thermo-mechanical treatment and by the addition of or admixture with other substances. He learnt for example that the properties of his clay were greatly improved by optimizing the water-content to improve its plasticity, by mixing-in straw/fibre and other particle-sized additives and then by glazing in fire to make it stronger and more aesthetic. As mentioned above, there is ample evidence that the early man was already smelting metals by 1000 B.C. In fact, the Biblical Cain was described as a worker of brass. Of course, he used what we now know as fundamental and powerful sets of materials engineering concepts, which can be said to be the very humble beginnings of metalworking/processing and composite materials technology, as we know it today.

However, it was only in the last couple of centuries that materials scientists and engineers were able to establish concise knowledge-based correlations between the elementary building structures or unit cells in materials and their bulk properties and hence were able to achieve successes in their performances/applications. This knowledge came with the advent of versatile research equipment and tools such as the metallurgical or inverted microscope, x-ray diffractometer, scanning and transmission electron microscopes (SEM/TEM), universal mechanical testing equipment, etc. Thus, it became possible for the materials scientists and engineers to design/fashion to a high degree of precision, characteristic materials to suit given applications. This revolutionized the materials and manufacturing industries such that hundreds of versatile materials – metals, alloys, non-metals and outstanding products were developed. This period can be said to have actually coincided with the industrial revolution periods in Europe and North America.

The modern-man has taken these initial knowledge-based materials technologies to much greater heights to develop tens of thousands of different materials, probably over 50,000 metals, non-metals, metal-based alloy materials and 'smart' materials. Today, man now has access to a myriad of categories of materials including laminated, particle and treated woods, metals and their alloys, special polymers, plastics and glasses, vitreous enamel, rubber, engineering ceramics-cermets, electroceramics, Functionally-Graded-Materials (FGM) composites, sol-gel, Micro/Nano-electromechanical Systems (MEMS/NEMS), Metal-Organic Frameworks (MOFs), carbon nano-tubes, wires, fullerenes, graphenes, etc. These engineering materials have through design, manufacture, assembly and quality assurance, become outstanding products – structures, machines, devices, tools, utensils, body-armor, weapons, airplanes, ornaments and innumerable other products that define the way we live today.

Today, materials are probably more deep-seated in our culture than most of us realizes. I wish to quote Afonja (1986) here:

> *"Perhaps the best way to appreciate the indispensability of materials to mankind is to review a few hours in a typical day in the life of an average modern man. He wakes up in the morning from a bed made of wood, steel and polymer, cleans his teeth with a brush made from polypropylene handle and nylon bristles, he takes his bath in an enamel plated steel bathtub, he dresses up wearing a nylon shirt, a terylene suit, leather shoes, and a quartz wristwatch. He takes his tea from a ceramic tea cup, or one drawn from an 18/8 grade stainless steel-jug and takes his breakfast with fork, knife, spoon of drawn and plated stainless steel. He drives to work in a car which comprises iron, steel, copper, aluminum, zinc, glass, plastics, rubber, and hundreds of other materials, listening to the news on his radio which is made of semiconductor transistors, silicon-based chips, metallic and ceramic resistors, etc. He signs into his office with a biro with at least five different materials – polyethylene for the ink holder, polystyrene for the shaft, polypropylene for the cap, copper alloy for the tip holder, and tungsten carbide for the tip/ball. This is only the beginning of a day during which hundreds of materials may be used. Indeed, man is always in contact with at least a major material at any moment in his life cycle. Clearly, materials play a very critical role in the existence and development of mankind"* – end of quote!

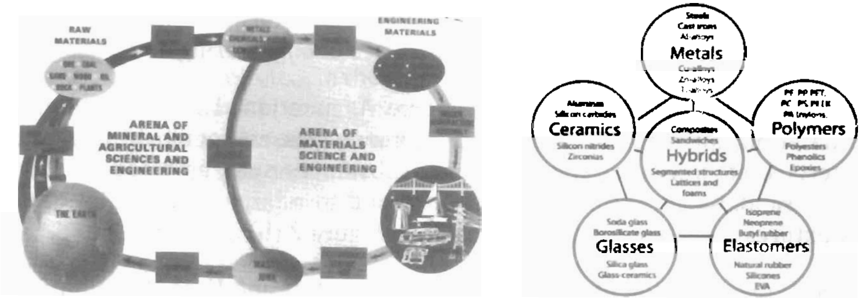
Furthermore, the modern day housewife has seen her kitchen transformed by progress in materials: aesthetic vinyl polymers in floor tiles; stainless steel in sinks; Pyroceram and Teflon in cookware (the type that assures that her cooked foods don't get burnt!). Today, a series of engineering and materials advances has yielded another important breakthrough innovation that offers megascale desalination by reverse osmosis, which is currently operational in Israel (Fonseca and Newton, 2015). This materials technology is able to produce clean water from the sea cheaply and at a scale never before achieved. It is expected to help provide fresh water from the abundant sea/ocean body of water for a world population that is growing fast. Thus, the contribution of materials development is indeed global. A number of developed countries such as USA, UK, Germany, South Korea, Japan, France, Norway and Sweden easily come to mind as countries that produce very high quality materials. These countries high GDP and GNP clearly indicate the role of materials science and engineering in their economic growth. In fact, by one of several possible reckonings, production, forming and application of materials account for some 20 percent of the US GNP, but this number is deceptive; without materials we would have no GNP! (The National Academies Press (1974); http://www.nap.edu/ read/10435/chapter/ 2#16).

It is therefore clear from the foregoing that everything we see and use is made of materials; cars, airplanes, computers, TVs, phones, refrigerators, microwave ovens, dishes, silverwares, athletics/sporting equipment, DVDs, biomedical devices and implants, etc. The materials engineers design/fashion/tailor, select and produce characteristic materials for these applications.

Adams and Pendlebury (2011) in their first Thomson Reuters Global Research Report to have a topical focus rather than a geographical one (i.e. based on World Science Map), have opined that the 21st century may well bring forth a new era of revolutionary discoveries in materials R & D that results in far reaching changes for society and how we live. The use and development of materials have contributed a major current in the history of mankind. The history of technology is replete with important milestones and examples of revolutionary change brought on by the discovery of new materials and new uses for materials. Bronze gave way to iron, then to steel and arguably now to silicon (which is indeed stronger than steel in the nano-regime!). The question now is: will graphene replace silicon in electronics? Will cars be fueled by hydrogen stored in MOFs? Will stem cells grown on nanofibrous scaffolds make organ replacement routine? The fact that we can pose these questions says something about recent advances in materials science and technology. It is suggested that we may now be truly entering a distinctly new 'Age of Advanced Materials'!

3. The Total Materials Cycle and the Materials Family

According to Figure 2(a), all materials move in a "total materials cycle", which is a global system whose operation includes strong three-way interactions amongst materials, the environment and energy supply and demand (The National Academies Press, 1974). The Figure is a schematic illustration of the materials cycle, showing the principal arena of materials science and engineering. The other areas shown are a myriad of possible sub-cycles including those related to environment and energy that were dealt with by Afonja (1986). From the earth and its atmosphere man takes ores, hydrocarbons, wood, oxygen, and other substances in crude form and extracts/win, refines, purifies, and converts them into simple metals, chemicals and basic raw materials. He then modifies these raw materials to alloys, ceramics, electronic materials, polymers, composites, and other compositions to meet performance requirements. The modified set of materials is subsequently shaped, worked, processed or machined for parts or assembly



(a) (b)

Figure 2 (a): Total Materials Cycle; (b): The menu of engineering materials. The basic families of metals, ceramics, glasses, polymers and elastomers can be combined in various geometries to create hybrids. (Ashby and Cebon, 2007).

into useful products. The product, when its useful life is ended, is discarded or junked and either re-enter the circuit again and again in one form or the other by recycling or reclamation or it eventually returns to the earth from whence it came or again to the atmosphere as waste, or where it may be dismantled to recover basic materials that re-enter the cycle. Thus like man, materials obey the time honored and biblical words:- "from the earth we come and to the earth we shall return"! Man has had to expend considerable energy in winning materials and even more energy in preventing or at least prolonging their return to the environment [mind you, I didn't say solely earth here, because some people are wanting to go and get minerals from the moon and even nearby planets!]. Thus you now hear of such sub-materials engineering disciplines as corrosion monitoring, prevention and control (CMPC), wear and/or tribology studies, recycling and waste management, as part of the modern concept known as the "Total materials cycle".

From the foregoing, it is clear that the total material cycle is an enormous enterprise requiring vast societal input in form of multi-disciplinary based knowledge, labour, energy and money for sustenance. In this way and at every stage around the materials cycle, there are strong interactions amongst materials, energy and the environment that enables some sort of equilibrium to be maintained. For instance, how do you assess the value of everyday things like plastic bags and 'pure water' sachets? Undeniably, they are a boon for carrying shopping and packaging drinking water but now also items of scorn for energy and waste (environmental hazards, etc.) reasons! In fact, the environment is known to have a profound effect on the behavior and performance of materials in service and indeed, most failures are attributable to environmental effects (nature, intensity and distribution of stresses, prevailing medium characteristics – corrosive, oxidative, elevated temperatures, low/cryogenic temperatures, radioactive, etc., media. New materials are being developed that can better resist these failure modes and improve the service delivery and performance of engineering materials.

Materials are indeed exceptionally diverse. As mentioned above, the family of materials spans metals, ceramics, polymers, glasses, composites (hybrid materials, etc.), natural and processed substances such as wood, rubber, fibers, sand, hydes and skin, stones, etc., and to a large extent, alloys and admixtures of these materials; as shown in Figure 2 (b) and Table 1.

Table 1: Classification of Materials, their Properties and Uses (Metallurgist, 2013)

Group	*Important Characteristics*	*Common Examples of Engineering Use*
Metals and Alloys	Lustre, Hardness, Resistance to Corrosion, Thermal and Electrical Conductivity, Malleability, Stiffness and Magnetic Properties	Iron and Steels, Aluminium, Copper, Zinc, Magnesium, Brass, Bronze, Invar, Super Alloys, Super-conductors, etc.
Ceramics/Composites	Thermal Resistance, Brittleness, Opaqueness to Light, Electrical Insulation, High-temperature Strength, abrasiveness, Resistance to Corrosion.	Silica, Glass, Cement, Concrete, Refractories, Silicon Carbide, Boron Nitride abrasives, Ferrites, Insulators, Garnets, etc.
Organic Polymers	Soft, Light in weight, Dimensionally unstable, Poor Conductors of Heat and Electricity, Ductile, Combustible, Low-thermal Resistance.	**Plastics** – Poly Vinyl Chloride, Poly Tetra Fluoroethylene, Polycarbonates. **Natural and Synthetic Fibers** – Nylon, Terylene, Leather, etc. **Other uses** – Explosives, Refrigerants, Insulators, Lubricants, Detergents, Fuels, Vitamins, Medicines, adhesives, etc.

Functional classification of engineering materials includes but not limited to the following:

- Aerospace
- Biomedical
- Electronic Materials
- Energy Technology/Environment
- Construction and Building Materials
- Magnetic Materials
- Optical and Photonic Materials
- "Smart" Materials
- (Nano)Structured Materials

The rapid developments in the fields of quantum theory of solids, mechanics of materials, microscopy and studies of materials structure-property relationships have opened vast opportunities for better understanding and utilization of various engineering materials. The spectacular success in the field of space exploration is primarily due to the rapid advances in high temperature and high-strength materials flowing from these fields.

According to the menu of engineering materials shown in Figure 2 (b), materials are used in one form or another, either in their pure elemental form (copper, silver, nickel, etc.), in the form of alloys and compounds (steel, brass, etc.), and still others in the form of composites and/or hybrids (cermets, fibre-plastics, fiberglass, wood laminates, etc). The selection of materials and the most appropriate manufacturing process routes depends on several factors, but the most important considerations are mainly shape complexity and properties of materials. The latter are ultimately linked with their microstructure and processing.

4. Materials, Minerals and Geo-Politics

It has been observed that either by sheer accident, providence or design, nature seemed to have located the bulk of the most strategic materials in the developing world, while the expertise for using them is in the developed world (Afonja, 1986). Of course, the latter had made sure that there is 'no resource control' of any kind and has had to wage serious wars under the guise of bringing civilization, in order to colonize territories and take away their valuable mineral/material resources. It must be mentioned here that some other developed countries like Japan, having lost out in the world wars, with no minerals and without access to conquered territories, became more pacific and turned to innovative ways of metal reclamation and recycling of war metal junks and extremely cheap imported metal scraps to shore up their materials requirements. Indeed, they made a resounding success of this enterprise technology, enough for the world to notice and import their cheap, energy efficient but quality products.

According to Afonja (2002), Africa's share of the world's mineral/material resources is quite enormous. Some of the world's best iron ores are located in Liberia and Guinea. Zaire has the world largest source of germanium and cobalt, while Zimbabwe has over 65 % of the world's output of corundum and 30 % of chromium, and holds a quarter of the world's reserves of lithium. Zambia has the world's most important sources of copper and aluminum, while Namibia has over three quarters of the world's uranium. South Africa has the world's largest sources of antimony, gold, platinum, rubidium, chromium, vanadium and diamond (gem). South Africa and neigbouring regions have most of the world's manganese and palladium. Nigeria has a significant proportion of the world's reserves of tin, columbite and tantalum. It should be mentioned here that columbite is a vital ferroalloy for the production of sophisticated alloy steels required for manufacture and construction of corrosion and heat-resistant chemical and heat-exchanger plants and equipment, superalloys for jet and aerospace engines. Tantalum is a major component in the production of capacitors, microswitches, etc., which are found in various everyday devices (mobile phones, video cameras, PCs and vehicle electronics). Furthermore, it is well known that the bulk of the world's source of petroleum/natural gas, the major raw materials for plastics, fertilizers, etc., is located in Nigeria, Angola, Latin America and the Middle East.

From the foregoing, it is clear why the political dynamics of African States is of vital interest to the developed world. Africa and a section of the 'developing world' hold very substantial reserves of strategic mineral/material ores! Interestingly, Zimbabwe apart from Russia, is the only source of chromium; an indispensible constituent of stainless steels. Zaire supplies the USA with about 50 % of her cobalt requirements, while South Africa supplies her with 66 % of ferrochrome, 44 % of ferromanganese (both very vital alloying elements in high grade steels), 89 % of chrome ore concentrate, 52 % of antimony, 37 % of vanadium (critical constituent of tool steels), 92 % of platinum, 85 % of asbestos and 98 % of manganese (Afonja, 2002). Little wonder then why the mineral/material ore supply is a very potent underlying factor in geopolitics and the associated inter cine wars! Indeed, recent development surveys have shown that despite the vital minerals discovered in Africa thus far, much of the continent is still unexplored and that there are indications that much of the mineral/material wealth is considerably more than have been established so far. The question that we should ask ourselves is why is Africa so endowed but so relatively poor? As a Professor friend in Germany told me about two and a half decades ago, apart from the self-inflicted inter cine wars and oftentimes very serious natural disasters that kept assailing the African continent, there has been very little effort by the "owners" of the mineral/material ore resources to add value to the resources and indeed they never seemed to have placed any value on these items! Most territories preferred to 'worship' and 'serve' these mineral/material ores as deities and ancestral forces to be worshipped. Thus, the African man found it easy to worship or hold in reverence, the perceived forces/power behind say the iron ore (mere inherent magnetic dipole and domain states' phenomena, etc.), flint, thunder and lightning (cloud dynamics manifested in light and sound), rather than to process and add value to them.

5. Frontiers of Materials Science and Engineering

As engineering design practices become increasingly stringent and sophisticated and service conditions more demanding, the need for novel and versatile engineering materials and components, particularly in conditions of high dynamic loading and adverse environmental conditions, is expected to increase. The critical role of engineering materials and indeed materials scientists and engineers in the building of a virile nation cannot be overemphasized. At the forefront of this development are the rather diverse disciplines of materials science and engineering.

The disciplines of materials science and engineering (of which the older metallurgy/metallurgical engineering is only a subset), have been at the forefront of these epoch making aforementioned technological developments and breakthroughs. Whilst, materials science lays emphasis on investigating the relationships existing between the structures (from elemental building blocks to the bulk state) and properties of materials, materials engineering on the other hand is based on stretching these structure-property correlations to include two or three other major legs of cost-effective fashioning, manufacturing/processing, testing, selecting and addressing potential applications, in order to design and/or engineer the primary structure of a material to yield pre-determined but outstanding set of desired properties. A critical aspect of materials engineering which deals with material selection and economics, involves cost-effective selection of materials for a given application from a wide range of options, based on the service requirements and conditions, processing, manufacturing requirements, corrosion-wear and mechanical behavior in service and failure analysis, economic and environmental requirements, etc.

Materials science is at the basic knowledge end of the materials knowledge spectrum and materials engineering is at the applied knowledge end, but there is no demarcation line between the two (Figure 3 (a)). Figure 3 (b) shows a three-stage diagram that illustrates the relationship among the basic sciences (and mathematics), materials science and engineering, and the other engineering disciplines. The basic sciences are located within the first stage or core of the diagram, while the various other engineering disciplines (mechanical, electrical, civil, chemical, etc.) are located in the outermost third stage. The applied sciences, metallurgy, ceramics and polymer science are located in the middle or second stage. Materials science and engineering is shown to form a **bridge** of materials knowledge from the basic sciences (and mathematics) to the engineering disciplines (000901.pdf).

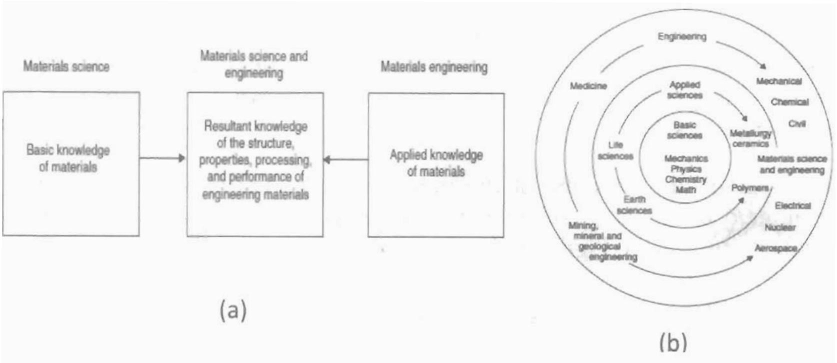


Figure 3: (a) Materials knowledge spectrum. Using the combined knowledge of materials from materials science and engineering engineers convert materials into useful products; (b): Materials science and engineering form a bridge of knowledge between the basic sciences and all engineering disciplines (www.000901.pdf).

From the fore-going, it is clear that all science and engineering disciplines must strive to know much more about materials. Even the most 'immaterial', like software or system engineering depend on the development of new materials, which in turn alter the economies, like software-hardware trade-offs. However, the increasing applications of system engineering are found in materials manufacturing (e.g. industrial engineering, machine language, robotics, etc.) systems.

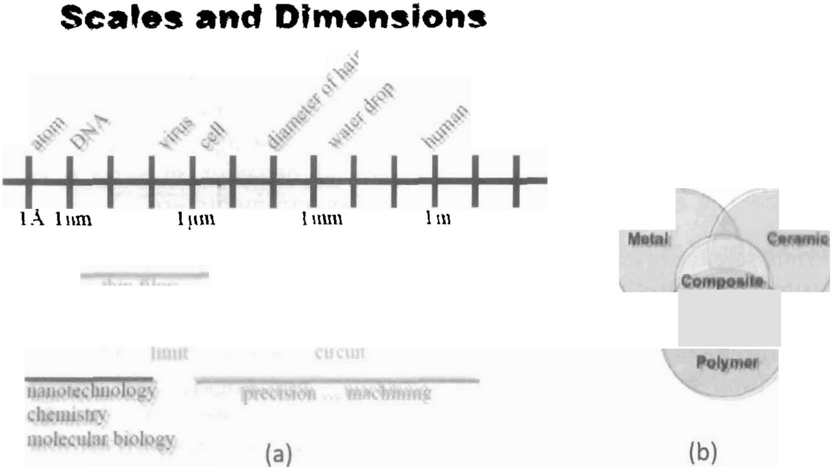


Figure 4: (a): Scales and Dimensions in Materials Science and Engineering; (b): Major Materials' Groupings (Kolesar, Jr. *et al* (2007))

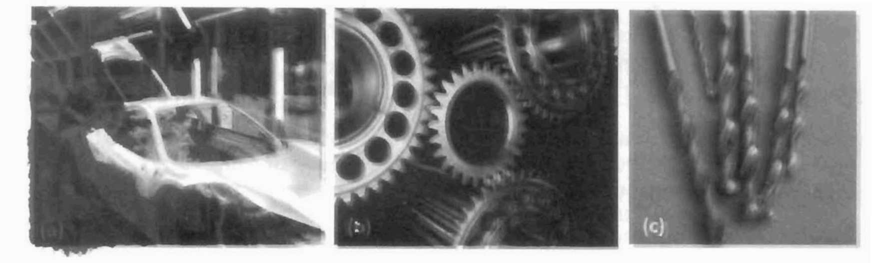
Today, techniques are being developed to establish performance indices, and materials selection charts, making materials selection considerably easier, more systematic and precise for all scientists and engineers. However, a strong materials education is still necessary for all science, engineering and even medical students, undergraduate and postgraduate alike; with a curriculum that emphasizes the four major but fundamental elements of structure, properties, processing and performance (applications) of engineering materials.

A brief background to some of the major areas of Training, Research and Development in materials science and engineering is presented below, with particular reference to Figure 4 (b):

5.1 Metallurgy/Metallurgical Engineering

Metallurgy and metallurgists remain the relatively oldest, heavily developed field and group, respectively, in materials research and development. According to Table 1, metals and their alloys are usually lustrous, ductile, malleable, and good conductors of heat and electricity. They are divided into two major categories: **ferrous** – the group which contains mainly iron (Fe); and **non-ferrous**: other metallic materials containing no iron like copper (Cu) or Aluminum (Al). These materials are used in one form or another, either in their pure elemental form (Cu, Ag, Ni, etc.), as components in alloys or as parts for assembly into products. The product, when its useful life is ended, returns to the earth or the atmosphere as waste or it may be dismantled to recover basic materials that re-enter the materials cycle.

There is enormous information garnered over the years in the field of metallurgy and metallurgical engineering such as in ferrous and non-ferrous metals extraction, winning and refining, their alloys, process modeling and simulation, development of new plastic forming technologies, energy saving production technologies, electrochemistry, corrosion and wear engineering, chemistry of metals, etc. These are still veritable areas of training, research and development. Over the years, new and emerging cost-effective technologies of metal and metal-alloy casting, casting machines, designs, mechanization and automation of foundry technology and practice, environmental impact assessment, protection and technologies of artistic/investment and precision casting, etc., have been developed and form current and active training, research and development areas in metallurgy/metallurgical engineering. Recent advances in technologies rely on sophisticated metallic materials. Thus, with the rapid advances in computer technology, design engineering and metal fabrication, joining and machining have also become quite sophisticated. Nowadays, mathematical models have been developed to study stress and process kinetics and computers are used to make detailed drawings, while machining and shaping processes are controlled by minicomputers (as in the now ubiquitous Computer Numerical Control (CNC) machines). The results have been quite outstanding (see Figures 5a-c).



Figures 5: (a) Car Aluminium body; (b) Reduction Gear System; (c) Cutting Tools (Galway Education Centre, 2013)

In particular, training, research and development activities in ferrous metallurgy cover the entire fundamental, theoretical, and application-related aspects of the metallurgical science and engineering as well as the technology of iron, steel, and their alloys. This special field traverses such areas as ferrous extractive metallurgy, pyrometallurgy, hydrometallurgy, powder metallurgy and processing, physical metallurgy, ductile iron and austempered ductile iron production engineering, corrosion engineering, thermal processing, metalworking, welding, iron- and steelmaking, heat treating, rolling, casting, hot and cold forming, surface finishing and coating, crystallography, metallography, computational metallurgy, metal-matrix composites, intermetallics, nano- and micro-structured metals and alloys, nano- and micro-alloying effects, special steels, and mining.

5.2. Ductile Iron (DI) and Austempered Ductile Iron (ADI)

In the last half century or thereabouts, the search for ferrous materials with significantly better machinability, high strength associated with good ductility, and a marked reduction in tool wear and cost has been centered on cast iron: the so-called 'yesterday's material', hitherto thought to be too brittle, as a potential replacement for high-grade alloy steels and niche aluminum alloys. Ductile iron (DI), also known as nodular or spheroidal-graphite cast iron (SGI) is the same cast iron in which the graphite is present as tiny spheres (nodules) instead of the rather 'weak' flaky form in gray cast iron. During solidification, graphite separates from the molten iron which contains special treatment additives and grows as spheres rather than as flakes in gray iron. Cast iron containing nodular graphite is much stronger and more ductile than gray iron of similar composition (Hornung and Hauke (1981); Mädler, (1999); Imasogie et al (2000, 2001, 2009); Imasogie (2003a, 2003b); Imasogie and Afonja (2003); Imasogie and Wendt (2004); Oluwole et al (2009); and Atanda et al (2013)).

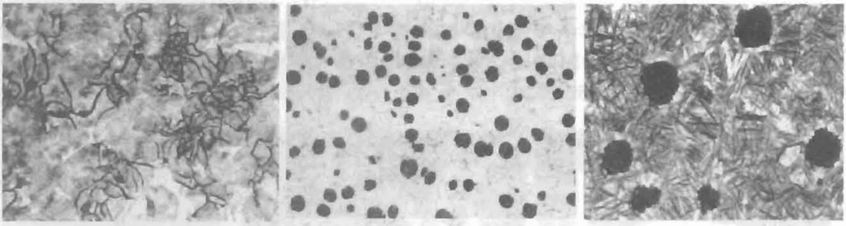


Figure 6: Microstructure of (a) Traditional Grey Iron with Weak Flaky Graphite Particles, x 100; (b) Ductile Iron with Spheroidal/Nodular Graphite Particles, x 100; (c). Austempered Ductile Iron with Nodular Graphite Particles in a "Steel-like" Matrix of Ausferrite and Retained Austenite (both Strong and Ductile Phases!), x 200. All 2 % Nital Etched. (Imasogie, 1994).

In recent years, DI the base material for the uniquely versatile austempered ductile iron (ADI), has become one of the most important ferrous engineering materials, in view of its excellent combination of good castability, machinability, and mechanical properties with significant savings in cost and weight compared with equivalent steel and other high-performance materials. The material can be tailored to fit an unusually broad diversity of needs, which remarkably has opened new vistas for its application in the manufacture of automobile, construction, communication, transportation, agricultural, mining, heavy-machine, military, and railroad components, which are traditionally produced by expensive forging and fabrication processes involving high-grade alloy steels and other equivalent high-performance materials. DI has strength, impact toughness, and ductility comparable to those of many grades of steel, while exceeding by far those of standard gray irons. It has the same advantages of design flexibility and low-cost casting procedures of gray irons (Imasogie, 2003b). Their corrosion resistance is equal or superior to that of gray cast iron and cast steel in many corrosive environments. Its wear resistance is comparable to some of the best grades of steel and superior to gray iron under heavy load or impact situations. DIs are considerably less expensive than cast steels to produce and only moderately more expensive than gray cast iron since the procedures are similar. It has a clear advantage over malleable iron for applications where low solidification shrinkage is required or where the section is too thick to permit uniform solidification as white or carbidic iron. Typical DI castings have advantages of isotropy of properties and homogeneity without laminations as in the case of steel forgings and fabrications and offer substantial cost savings, particularly with respect to the reduced requirement for feed metal, production cost (in terms of material and energy requirements), and mechanical properties. Again, the use of the most common grades of DI "as cast" eliminates heat treatment costs, offering a further advantage. It is well known that the presence of graphite contributes directly to lubrication of rubbing surfaces and provides reservoirs to accommodate and hold lubricants. This means good resistance to mechanical wear. Graphite also contributes to machinability because it acts as a lubricant during cutting and also tends to break up chips. Like gray iron, ductile iron has inherent corrosion resistance. In addition, the spheroidal graphite has desirable lubricating and crack arresting effects in the system (Imasogie et al (2000, 2001); Al-Ghonamy et al 2010)). DI is a near-eutectic alloy, which means that it has a low melting point, high fluidity, and good castability especially for intricate, complex-shape castings with light sections. Expectedly, the automotive industry has expressed its confidence in ductile iron through the extensive use of the material in safety-related, functional, and structural components such as steering knuckles and brake calipers, which are used mostly as cast.

The fact is that all these advantages are due one way or the other to the inherent presence of graphite in the system and better still, if it is wholly in the spheroidal form. It has been established that all of the mechanical properties characteristic of DI are as a result of the graphite being substantially or wholly in the spheroidal/nodular shape. The bulk mechanical properties are thus determined primarily by the steel-like matrix, and any departure from this shape/form or in the proportion of the graphite will cause a drastic deviation from these properties (Imasogie and Wendt (2004)).

The most important single step in the production of DI is the addition of graphite-nodularizing agents in the treatment of the iron melt. DI results from a suitable treatment of the molten iron with cerium, magnesium, and/or magnesium–calcium containing treatment agents, prior to casting, which causes the graphite to precipitate as tiny spheroids or nodules rather than as flakes, as obtained in the case of gray cast iron (Fig. 6: a-c (Imasogie, 1994); Imasogie *et al* 2000). Apart from the graphite being wholly in the spheroidal shape, it is noted that a significant number of nodules are required in order to avoid the formation of intercellular carbides during solidification, especially in thin-walled castings, due to the high solidification rate. From metallurgy point of view, the graphite nodule count and distribution affect the ferrite/pearlite ratio and content of the matrix and hence on notable mechanical properties such as impact and fatigue strengths.

Recent global interest in austempered ductile iron (ADI); the newest and most versatile member of the engineering purpose cast iron family, has markedly increased in the past two decades as increasingly successful applications, particularly as economic substitutes for the rather expensive high grade alloy steels are being reported (Keough (2001); Hayrynen et al (2002); Guesser et al (2012)). It is interesting to note that ADI is essentially cast iron, engineered in two ways. Firstly, as in DI production, the graphite is nodularised and its stress raising ability completely modulated. Secondly and most importantly, the structure of the matrix surrounding the free graphite nodules is engineered, depending on the applied isothermal heat treatment schedule and conditions, to produce a specific austempered 'steel like' microstructure consisting of acicular, carbide-free ferrite (ausferrite) with controlled amounts of retained austenite (an fcc ductile phase) (Yescas-Gonzalez (2001); Imasogie and Afonja (2003)). Thus, apart from substantial cost savings in the production of the primary DI material compared with steel, an ADI designed engineering component can save cost at each stage of manufacture because of its excellent castability, lower machining cost, lower density than steel, strength comparable to that of steel, and excellent fatigue strength.

The major advantages of austempering heat treatment are: (a) good control of the transformation process and (b) freedom from residual stress, distortion and cracking associated with rapid cooling from the austenitizing temperature to room temperature (Imasogie (2000); Imasogie and Afonja (2003)). ADI has a wide range of unique and desirable, but hitherto incongruous combination of engineering properties, such as hardness/wear resistance, toughness, ductility, machinability coupled with significant savings in cost and weight, compared with equivalent steel components. Expectedly, considerable research is being undertaken to harness the great potentials offered by this combination of properties for improving productivity, performance and cost. Compared to steel, ADI exhibits superior functional properties in terms of machinability, tool life and machining speeds, surface finish, resistance to scoring and wear, improved safeguard against failure (due to the lubricating effect provided by graphite); better resistance to contact fatigue (because of its much lower E); damping capacity and hence better noise attenuation, amenability to heat treatment, lower density and hence better weight reduction, energy savings and other cost requirements, from molten metal to finished product. Also, ADI castings can have uniform properties even with complex shapes, a characteristic not always possible or economical with steel forgings or weldments (Brandenberg et al (2001); Guesser et al (2012)). Developments in ADI have made it possible to replace such costly engine components as camshaft, crankshaft, connecting rods, axle shaft, steering knuckles and tractor parts of forged steel with ADI castings. The prospects of ADI as alternative material to the rather expensive, forged, case-hardened, high-alloy steels in other critical components operating under severe dynamic conditions, such as hypoid rings, pinions, bearing and toothed gear power transmission (since it is significantly machinable for the teeth to be cut after the heat treatment, thus giving the best possible dimensional accuracy), is expected to open new vistas for ADI application. Furthermore, major engineering components requiring complicated manufacture from high grade alloy steels by e.g. forging, rolling, welding and surface hardening, all of which may preclude the use of normal machine tools, can now be made in near-net shape castings in ADI.

A very wide range of automotive components is now being produced commercially in ductile or austempered cast iron. These include crank shafts, brake calipers, steering knuckles, connecting rods, gear wheels (see Fig. 7 (Brandenberg et al (2001)). Pipes and pipe fittings used in petroleum pipelines, industrial and domestic water distribution, sewage pipeline networks, are now mostly made of ductile iron.

Ductile iron castings can replace other materials and manufacturing processes with either an improvement in performance or lower production cost, or both. In some applications it can offer up to 50% cost reduction as well as an overall component weight reduction, even for aluminium (Guesser et al (2012)). ADI is ideal for a number of high-strength, low-wear applications, for example, as an alternative to expensive high-alloy steel for gears, pinions and sprockets in high speed (e.g. Formula 1) - racing cars.

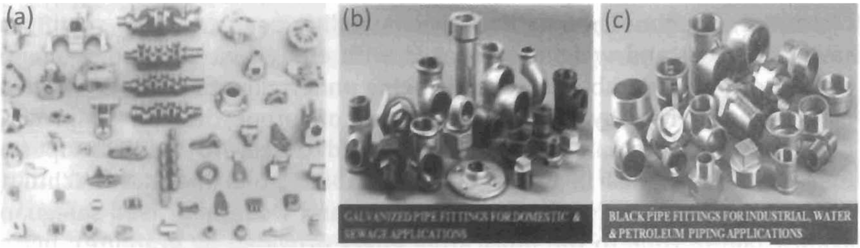


Figure 7: (a) some DI and ADI Components on a Toyota Vehicle; (b) DI Galvanized Pipe Fittings and (c) DI Black Pipe Fittings (Brandenberg et al (2001)).

Mr. Vice-Chancellor sir, I am glad to mention here that I have been opportuned to contribute a chapter on spheroidal graphite irons (SGI) and their characterization in the recently published CRC Press-Taylor & Francis': 'Encyclopedia of Iron, Steel and their Alloys', edited by Colas and Totten (2016). This Encyclopedia is a valuable reference for materials scientists and engineers, chemists, physicists, manufacturers, miners, researchers, and engineering students, and it provides extensive coverage of properties and recommended practices, protocols and includes a wealth of helpful charts, nomograms, figures and contains cross referencing links for quick and easy search. The five-volume, sixty-five-chapter resource material set has each entry written by a subject-matter expert and reviewed by an international panel of renowned researchers from academia, government, and industry.

Mr. Vice-Chancellor sir, the DI-ADI research group at OAU, Ile-Ife, Nigeria has spent the last few years researching all aspects of the subject. I am a team leader in most of the projects. The group now has the required expertise to develop a simple ductile iron and austempered ductile iron foundry practice and protocol capable of producing industrial quality components, and we are ready to transfer the technology to existing indigenous foundries and prospective entrepreneurs.

5.3 Non-metallic Materials and Composites

5.3.1 Ceramics and Glasses

The word ceramic is derived from the Greek word "keramikos", and covers inorganic non-metallic materials whose formation is due to the action of heat. Major examples are clays, bricks, cements, glass, etc. As engineering materials, ceramics offer unique properties, notably exceptionally high hardness and resistance to wear/abrasion and corrosion as well as high temperature properties that are considerably superior to those of any metal. However, they are generally less ductile, intrinsically brittle and susceptible to thermal shock which in turn can limit their maximum service temperatures in applications involving thermal cycling (IAEA, 2012). Engineering ceramics currently include: (i) alumina, (ii) beryllia (beryllium oxide) and boron nitride, (iii) porcelain (aluminum silicates), (iv) steatite and forsterite (magnesium silicates), (v) silicon nitride and silicon carbide, (vi) titanium diboride and (vii) vitreous carbon.

Fabrication of ceramics does not pose much difficulty since they can be formed by traditional techniques such as slip casting, wet pressing and extrusion. Modern forming methods include injection molding, iso-static pressing, tape casting and dry (hydraulic) pressing.

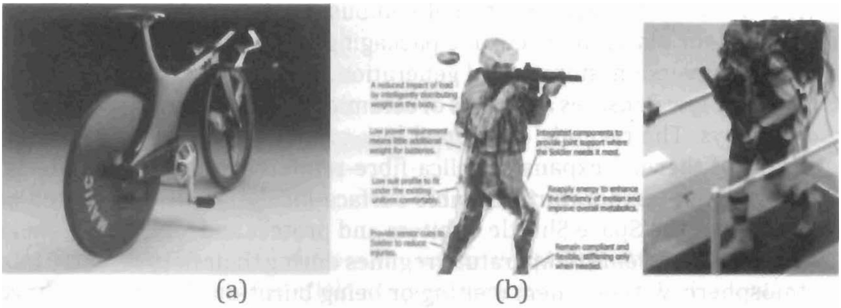
Modern applications of engineering ceramics include niche uses in the fabrication of electronic components, engineering components, medicine, dentistry and jewellery. In particular, ceramic coated metals and ceramic-metal combinations have niche applications in nuclear reactors and jet-engine manufacture. It should be mentioned here that the mechanical properties of such metal-ceramic (cermets) composites are quite in the extremes. Most cermets are fabricated by techniques akin to powder metallurgy, involving refractory oxides, carbides or nitrides, while the metal powder component may include chromium, nickel, molybdenum, titanium, etc. The resulting properties are usually significantly different from those of either of the separate constituents. Some cermets have exceptionally high melting points, which are best realized in an open flame (IAEA, 2012).

Current research centered on new engineering ceramics involves modeling and simulations to better understand the fundamental character of these materials and of the phenomena that occur in them, resulting in their unique properties. Studies involving electrical, magnetic and optical properties and property combinations unique to ceramics are being carried out to fashion out new products for use in internal combustion and turbine engines, as military armour plates, in electronic packaging, as special cutting tools, and for energy conversion, storage and generation. In the case of turbine blades, the relatively low densities and costs of ceramics make them more preferable to superalloys. The recently developed low-conductivity, low-density, low-coefficient of thermal expansion silica-fibre-reinforced insulation material (known as 'high-temperature-reusable-surface-insulation; HRSI) is used in tiles that cover the Space Shuttle Orbiters and protect and/or insulate them from the rather extreme temperature regimes during their fiery re-entry into the atmosphere, without them melting or being burnt-out. Techniques have also been developed to improve the low fracture-toughness of ceramics. In the new ceramic-matrix-composites (CMCs), fibres, whiskers, particulates, etc., of one ceramic material are embedded in a matrix of another ceramic material, resulting in beneficial interaction between advancing cracks and the dispersed phase particles. The result is a greatly improved fracture toughness property of the product. The new set of 'Hybrids' (multi-fibre-reinforced composites) have better all-round combination of properties than single-fibre reinforced types. The glass-carbon-fibre hybrid is relatively stronger and tougher with a higher impact resistance and lower cost than the conventional all-carbon or all-glass reinforced composites. Also, the recently developed family of ceramic superconductors with extremely high critical temperatures permits the use of inexpensive liquid nitrogen (in comparison to conventional liquid hydrogen and helium) as coolant in cryogenic temperature applications.

Glass is grouped with ceramics as a class because it has similar properties but most glasses are amorphous and brittle in the bulk state. However, recent R & D efforts in glass technology have yielded glass-based materials that can bounce and others that can be fitted to armor personnel carriers, etc.

5.3.2 Composite Materials

A composite material is a system or a combination of two or more chemically distinct, somewhat insoluble materials whose union results in a new material with specific properties, characteristics and attributes superior to its constituents, acting independently. In a number of novel composite materials systems, a stronger, sometimes fibrous or particulate material is usually combined (e.g. by bonding) with others to reinforce or strengthen the resultant mass. A composite is designed to display a combination of the best characteristics of each of the component materials. Composites generally exhibit high strength/stiffness to weight ratios and as such they are widely used in the aerospace industry, marine and offshore structures, boats, sporting goods, etc. Typical examples of engineered composite materials are wood laminates, clad metals, fibre glass, reinforced plastics, cemented carbides, etc.



(a) (b)

Figure 8: (a) Olympics Gold Winning CFRP Lotus Bike (Courtesy: Lotus Engineering UK); (b) Tactical Assault Light Operator Suit (TALOS), (***abc*** News, 2013)

For example, modern tennis racquets, pole-vaults and sporting bicycles are made of carbon-fiber reinforced plastics (CFRP) composites. CFRPs were at the heart of the LOTUS bike (Figure 8 (a)) built by Lotus Engineering for the

1992 Barcelona Summer Olympics UK entrant. It helped Cyclist Christopher Miles Boardman; MBE, of Great Britain win gold in the men's individual cycling pursuit (www.chrisboardman.com, 2015). Boardman was both Olympic Champion and World Record Holder in Men's 4000 metres individual pursuit event at Barcelona. The Lotus bike later became a reference point for modern sporting bike monocoque design, although it remained a proprietary work. Unfortunately, in March 2016, it was reported that Boardman had eight of his exotic bikes and some scuba diving equipment stolen from his Merseyside home following an overnight burglary (www.cyclingweekly.co.uk, 2016).

Figure 8 (b) shows the special US Army's Research Development and Engineering Command (RDECOM) designed 'iron-man-like' body armor for soldiers called the: Tactical Assault Light Operator Suit (TALOS). TALOS is designed to add armored protection for special operations soldiers without adding excessive weight (ABC News, 2013). The TALOS technology is novel in that it uses a special light nanomaterial magnetorheological (MR) fluid, which relies on magnetic fields that can be varied to create different degrees of hardness and flexibility. The shear-thickening fluid (itself a smart material), which reacts to a force or impact (e.g. a speeding bullet), by hardening to strengthen the soldier's body armor. TALOS protective capability is in its ability to combine several technologies, such as physiological sensors and power supply batteries, into a single piece of armor equipment.

Today, nano-composites are exciting new materials with novel properties and it is a fast growing field of materials research with broad scientific interest and extremely impressive technological promise. Products include self-healing rubber tyres, super-absorbent material that soaks up oil spills, super-tough willow glass, fire-resistant fibrirock tiles and recently, the Quantum Tunneling Composite (QTC), which depicts insulative properties on one side and conductive properties on the reverse side. Also, current engineering nano-composites R & D focus has been on cost reduction and high precision production processes, batch fabrication, with improved impact and fatigue characteristics, since their inherently complex, non-plastic behavior are often difficult to model and/or predict.

5.3.3 Polymeric (Plastic) Materials

Most polymeric materials consist of organic (containing derivatives of carbon-hydrogen) with long molecular chains or networks. They are non-crystalline structurally, but may consist of mixtures of crystalline and noncrystalline regions. Polymeric materials generally have low densities and relatively low softening or decomposition temperatures. They are usually classified into three main categories, namely; thermoplastic polymers, thermosetting polymers and elastomers (or rubbers). Generally, polymeric materials are poor conductors of electricity.

However, in the last couple of decades, novel polymeric materials have been synthesized that have electrical conductivities on par with metallic conductors, even as high as one-fourth that of copper on a volume basis, but twice its conductivity on per weight basis. A special set of polymers doped or impregnated with appropriate impurity agents (dopants) have been developed, including polyacetylene, polyparaphenylene, polypyrrole and polyaniline. Depending on the specific dopant and mode of processing, these polymers can be made either n-type (i.e. – free electron dominant) or p-type (i.e. – hole dominant) or even in an appropriate system combination of both, akin to semiconductor devices. Because of their ease of production, low densities and high flexibility, they have potential for use in electronic packaging, paper-like displays, rechargeable batteries (using polymer electrodes), aircraft wiring and components, anti-static coatings for clothing, electromagnetic screening materials and novel electronic devices and components (transistors, diodes, digital video disks, etc.). Recent research and development efforts have been geared toward polymer-based nanocomposites which are now being developed for electronic applications such as in thin-film capacitors in integrated circuits and solid polymer electrolytes for batteries (002212.pdf: Retrieved December, 2014).

5.3.4 Electronic/Magnetic/Optical/ICT Materials

This set of engineering materials has experienced a phenomenal revolution in the last 5-6 decades, which has impacted virtually all aspects of technological development. From the startling contributions of the early 'Silicon-Valley' days, materials scientist and engineers in the late 1940s (the invention of the transistor in 1948 was indeed a milestone in the history of technology) to latter strides in microelectronics and now to modern nanoelectronics (and allied magnetic, optical, etc., systems), it has been one innovation after the other, in electronic, magnetic, optical, solar energy and ICT devices and systems. Since the last quarter of the last century, it has become possible to produce ultra-high purity single crystals of silicon, germanium and other derivatives required for transistors, diodes, etc., Commercial production of these items was actually a result of years of intensive research into metal purification by zone refining and single crystal technology. Furthermore, the development of semiconductors has made possible the advent of integrated circuitry that totally transformed the electronics and computer industries in particular, and the manufacturing industries in general. The devices have become more sophisticated, compact, robust, etc., user-friendly and environmentally compliant. For example, research on the familiar light-emitting diode (LED) used in digital displays has led to the development of a new LED based on gallium nitride and allied inorganic compounds, which is now being used in cost-effective lighting systems. According to Afonja (2002), if a country like the United Kingdom were to switch from conventional light bulbs and fluorescent tubes to the new LED lighting units, the country would save as much as 10 % of her entire energy consumption. The only 'problem' is that LED-based internal light 'bulbs' would last for up to 60 years and, in the words of Professor Colin Humphreys of the University of Cambridge, UK., people could forget even how to change them!

From the foregoing, it can be said that the phenomenal development of the electronics and allied industry in the last sixty years or thereabouts is a direct result of progress in materials technology. The materials engineer has been at the fore-front of these developments and also in the development of the technology of fabrication and assembly of devices, manufacture of robust resistors, capacitors, insulators, and etching millions of transistors, diodes into novel processor chips, and integrating and/or incorporating the chips in modern polymer-based systems. We now have computer hard disk storage data capacity that has increased phenomenally by a factor of 10,000 compared with the initial floppy drives. Today, optical CD-ROMs, micro-fiche, etc., which have data capacity of over 5 x10^6 floppy HD-diskettes are available. The development of the CD and DVD, LCD, LED, etc., has revolutionized the music and video world. Fibre optic and wireless telecommunications, electronic mail, the internet, etc., are a few other developments which are heavily dependent on developments in materials technology.

5.3.5 Smart Materials

Smart or intelligent materials form a unique group of new and state-of-the-art materials that have significant influence on many modern day technologies. Being 'smart', these materials are able to sense changes in their environments and then respond to these changes in predetermined and measurable manner, like living organisms. The field of smart materials attempts to combine in one integrated unit, the 'sensor' (that detects an input signal), an 'actuator' (that performs a responsive and adaptive function) and the 'control' circuit (Figure 9 (a)). In particular, the actuator can change shape, position, natural frequency, or mechanical characteristics in response to changes in say temperature, pressure, electric, magnetic fields, etc

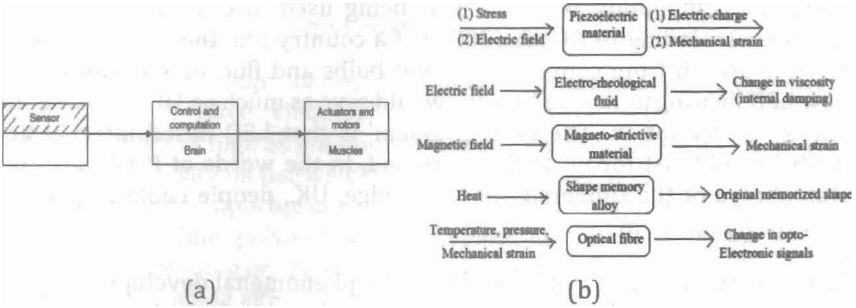


Figure 9: (a): Integrated Sensor-Actuator Systems with Controller - Analogous to Biological System (002212.pdf); (b): Common Smart Materials and Associated Stimulus-Response (Kamila, 2013).

(Figure 9 (b)). Examples of such actuating materials are shape-memory alloys, piezoelectric ceramics, magnetostrictive materials, and electro-rheological/magneto-rheological fluids. Notable smart-material products are accelerometers (for the deployment of airbags), microsystem technology (MST), micro-electro-mechanical-systems (MEMS), optical fibres, micro-piezo-electric devices, robotics, etc. MEMS devices are known to be compact or small in size, light weight, low-cost, reliable with large batch fabrication technology. Other examples of smart material devices are metal springs, light bulbs self-actuation, etc.

Current areas of R & D in smart materials technology include the Bio-inspired Plastic (BIP) materials. Such materials are light enough to permit flight, thin enough to accommodate flexibility and strong enough to protect its host; natural insert cuticle – found in the rigid exoskeletons of houseflies and grasshoppers. It is made with this naturally inspired concept in mind, and can be used to study insects, birds and animal migratory patterns as well as ecological and weather situations.

5.3.6 Biomaterials

Biomaterials are a set of biocompatible and if necessary and required, biodegradable and implantable materials, that include selected metals, ceramics, polymers, composites and semiconductors, used in major human body replacement parts, target treatment and devices (pacers, traction and tracers components, etc.), drug delivery, scaffold, etc. Special materials are selected with requisite characteristics, such as good stress and corrosion (including major modes; uniform, crevice, pitting, fretting, stress-corrosion-cracking (SCC), corrosion fatigue, etc.) resistance, to be used as biomaterial implants, pacers, etc. The human hip-implant is a good example of the way specific materials are integrated to achieve a functional "spare part", as shown in Figure 10 (Mukasyan (2014)). Optimal materials that meet mechanical and chemical characteristics of the implant portion and/or general body are selected for basic parts of femoral stem, the ball attached to the stem, the acetabular cup affixed to the pelvis and a fixation agent used to secure the stem into the femur and the cup to the pelvis. Two specially engineered materials, namely; cobalt-nickel-chromium-molybdenum alloy and titanium-vanadium alloy are often selected as optimal materials for the femoral stem because of their mechanical, corrosion and fatigue properties and biocompatibility (Afonja, 2002). Metal-ceramic composites with good fracture toughness and fatigue resistance have been developed for the ball component. The acetabular cup has a virtually inert ultra-high molecular weight polyethylene as one of the optimal materials because of its excellent wear resistance and low-coefficient of friction characteristics. The fixation agents include polymethyl methacrylate (acrylic) bone cement that is polymerized in-situ during the implant surgery. However, a recent development in the use of porous, metal powders have been reported, in which after implantation, bone tissue grows into the three-dimensional pore network, and thereby fixates the implant to the bone (Mukasyan (2014).

Recently, biomedical materials engineers at Duke University, USA, have grown living skeletal muscle that looks a lot like the real thing (Careercornerstone.org, 2014). The material contracts powerfully and rapidly integrates into mice quickly, and for the first time, demonstrates the ability to heal itself both inside the laboratory and inside an animal. The materials engineers tested the bioengineered muscle through a novel real-time monitoring through a window on the back of a living mouse and observed the muscle's integration and maturation.

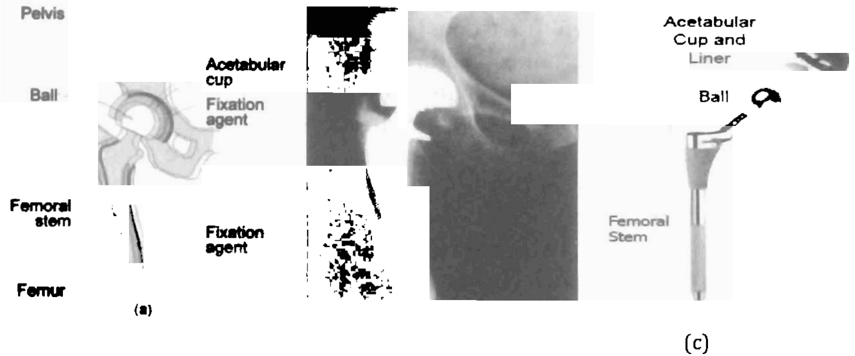


Figure 10: Human HIP Implant System. (Mukasyan (2014).

The research team worked on actualizing and integrating two major aspects of the work, namely; a well developed contractile muscle fiber and a pool of muscle stem cells, known as satellite cells. They successfully created the microenvironments; called niches, where these stem cells await their call to duty. This process has been shown to successfully 'vascularise', 'innervate' and repair damaged muscle's function. The research has been acclaimed as an important step towards growing viable muscles for studying diseases and treating injuries and represents an important advance for the field of materials science and engineering.

Other emerging research and development areas in biomaterials engineering include tissue and implants made of special re-absorbable polymers and composites, artificial pacers, cleansers, pumps, etc., for heart, kidney, liver and eye, with requisite traction components. Also, novel biomolecular drug delivery systems using coated nanocrystalline ceramics are being developed for controlled delivery of biochemically active molecules (enzymes, drugs, etc.) of different classes of activity into the human body. In particular, the molecules in these conditions are known to exhibit prolonged biological activity and elicit strong immune responses in the body. This development is opening up a whole new route to vaccines, synthetic blood, drug delivery, gene therapy, etc.

5.3.7 Nano-Materials

Mr. Vice-Chancellor sir, the field of nanomaterials and nanotechnology represents the most modern and promising research and development areas in materials science and engineering. There have been rapid theoretical, experimental and practical application developments in new production technologies of single crystals, nanopowders and ceramic nanocomposites, synthesis and characterization of organo-metallic precursors for oxide and non-oxide nanomaterials (as the work of the OAU team led by Professors E. O. B. Ajayi, T. A. Kuku, G. A. Adegboyega, O. Osasona, G. A. Egharevba, W. Siyanbola, etc., has shown (Osasona (2015)). New alloys of nanometric microstructures, epitaxial nanostructures, layers and magnetic materials, carbon nanotubes and wires, graphene, fullerene, etc, have been developed. Recent research in nanomaterials have been focused on in-depth studies on mechanisms controlling phase transitions, microstructure and crystal structure control in metals and non-metals, alloys, powder metallurgy, non-destructive materials testing, evaluation and characterization, material defects, processes of plastic strains, surface engineering, single or monocrystals, nano-composites and lately, research into noble metals. Furthermore, engineering nano-ceramic materials have recently been receiving significant attention in cognitive R & D; particularly in the spheres of ceramic white-wares, tiles, sanitary-wares, building, coating and cladding materials, refractory, cementing agents, insulators, concrete, glass, enamel, electroceramics, thermoelectric and magnetic materials, energetics (materials for alkaline and solar batteries, fuel cells, etc.), optoelectronics (electronic and amorphous coating, carbon fibres, MEMS and NEMS, etc).

Nanostructured (NS) and nanocrystalline (NC) materials have microstructural features in the 1 – 100 nm range in at least one dimension. They have outstanding physico-mechanical properties due to their extremely fine to ultra fine grain size and high grain boundary volume fraction, high aspect ratios, etc. In the literature, nano-material formats include: groups of nanometric atoms called nanoclusters, nanoparticles, nanocrystals, quantum dots, or boxes, nanowires, nanotubes, etc., depending on the characteristic features, while both atomic and molecular formats include; bucky balls and fullerenes, bulk nanostructured metals, magnetic nanoparticles/nanostructures, nanobelts, nanolubricants, nanocrystals and powders, nanofillers, nanoadditives, nano-dispersions, nano-rods, nano-sponge/abrasives and 'Reactive Electro-Exploded Nano-powders (REEN-Powders). However, research has shown clearly that NS and NC materials exhibit properties which are significantly quite different from their bulk-material properties. For example, silicon wafer is extremely brittle, but single-nanocrystal silicon is ~ 10^3 stronger and tougher than steel. Generally, materials produced out of nano-particles, wires, tubes, etc; have some special features such as (i) very high ductility, (ii) very high hardness (~ 4 to 5 times higher than in conventional materials), (iii) transparent ceramics achievable, (iv) manipulation of colour, (v) extremely high coercivity magnets, (vi) developments of conducting inks and polymers and (vii) 3-D printing enabling (002212.pdf). Furthermore, an emerging domain in Nanomaterials called 'Nanomaterials by severe plastic deformation (SPD) is now of current R & D interest and it involves the cost-effective application of very high strains and flow stresses to work pieces. These processes result in positive-yielding microstructural features and properties in materials (notably metals and alloys), far in excess from those expected for conventional cold-worked materials. Such efforts have resulted in the achievement of special pore-free grain refinements down to nanometer dimensions and dislocation accumulations up to the limiting density of ~ $10^{16}m^{-2}$. SPD yields an increase in ductility without a substantial loss in strength and fatigue resistance. Furthermore, superplastic flow at strain rates significantly faster than in conventional alloys, thereby enabling the rapid fabrication and prototyping of complex components and parts have become achievable. The magnetic properties of severely plastically deformed materials are different from those of conventional materials, while achieving enhanced zamanence in hard magnetic materials, decreased coercivity (i.e. energy loss) in soft magnetic materials and induced magnetic anisotropy. The result has been an outstanding extension into new realms, territories and trends in the field of materials science and engineering.

From the foregoing, emerging NS and NC materials have immense potential for high technological engineering applications. Also, the appropriate mixing of nano-particles with polymers to form nanocomposite materials is yielding engineering materials of potential technological value. We now have nano-particle-toughened automobile tyres prepared by blending carbon-black, zinc oxide and magnesium sulphate particles with vulcanized rubber. The result is the "self-healing" tyres that are making waves today. It should be mentioned here that the journey into the great potentials of the nano-world actually began in the early 1990s, when it was first reported that adding mica to nylon produced a five-fold increase in both the yield and tensile strengths of the material. This completely revolutionized the polymer-nano-particle composite materials industry with subsequent surge in R & D of nanostructures, semi-conducting materials (e.g. metal chalcogenides and nitrides).

Mr. Vice Chancellor sir, the current interest in both academic and industrial sectors in NS and NC materials arises in part from the remarkable positive variations in fundamental electrical, magnetic, optical and thermal properties that occur as one progresses from an 'infinitely extended' solid to a particle of material consisting of a countable number of atoms (002212.pdf). The focus is now shifting from synthesis to manufacture of useful, high performance and environmentally benefiting products; structures, coating and cladding materials having greater wear and corrosion resistance properties. Of course, the other part of this positive effort is supplied by the tremendous efforts of national R & D funding agents, materials technology policy initiators, governmental committees and foundations charged with overseeing this tremendous enterprise.

5.3.8 Advanced Materials

These are materials used in "High-Tech" applications, usually designed for maximum performance, for use in sophisticated and specialized electronic equipment, robotics, military rocketry, super-computers, fibre optics, supersonic aircrafts, spacecrafts, nuclear energy, solar energy, etc., but are mostly very expensive. They are either traditional/conventional materials whose properties have been enhanced or are entirely new engineering materials that exhibit specific set of desired properties such as high strength and hardness, good thermal, electrical, magnetic, optical or chemical properties. Engineering materials from either groups are high-performance materials which may cut across all materials classifications – metals, ceramics, composites, glasses, polymers, etc. Notable examples are novel titanium alloys for supersonic airplanes, magnetic alloys for computer disks, special ceramics for the heat shield of space shuttles, etc. The development of some other advanced materials that have significantly altered communication technologies, enhanced military weapon delivery systems, improved data analysis, restructured medical devices, advanced space travel, etc, while many transformed industrial production processes have been reported. They are usually highly and systematically processed and possess high value-to-weight ratios. They are often combined into new and novel composites. A another good set of examples of advanced materials is the group known as "functionally graded materials", - graded by either chemical composition, density, second phase particles or fibers in a matrix, microstructural features, coefficient of thermal expansion, etc. Thus, instead of a step-functionality, it is often desirable to have gradual change that will reduce the chances of developing mechanical and thermal stresses in service, hitherto prevalent. A lot of research and development work is going on with this class of materials particularly in the coining, jewellery and indoor ornaments and packaging, military weaponry, space exploration, telecommunications, etc, industries.

5.3.9 Materials in Transportation

Transportation is one major area where human development seemed to be heavily dependent on appropriate engineering materials' inventions. Modern mode of transportation started with the development of the steam engine during the second half of the 19th Century. This was as a result of the pioneering work of inventors; Messrs Denis Papin (1679), Thomas Savery (1698), Thomas Newcomen (1712) and James Watt (1765), who made an improvement on the work of the former three inventors. Appropriate materials which were resistant to both the highly corrosive steam and high temperature oxidation were developed for various vital components – the fire chamber (with cast iron), the steam boiler (alloy steel), the piston/cylinder assembly (various grades of cast iron and alloy steels), etc. The railway system soon followed, with the development of strong and wear resistant grades of cast iron and steels for the wheels and rail tracks, and rolled flat sheets for the cabins, etc. Again, the automobile industry which became viable in the mid-nineteenth century required specially selected materials for engine components, chassis, body, braking system, tyres, etc. A modern motor vehicle is made up of over 2000 different materials, all appropriately integrated into a functional unit (Afonja 2002). While the body and fenders are made of mild steel (hybrid materials in newer models), the crank-shaft, gears, connecting rods, valves, etc., are of forged grade of alloy steels or recently, the much cheaper and versatile ductile iron and austempered ductile iron (DI and ADI) materials, the pistons, cylinder-head, block, are made of compacted graphite iron (CGI) or reinforced aluminum-magnesium-silicon alloy. The pinions, rings and sleeves are of ductile irons, and the gear selector-fork is a copper alloy or aluminum-bronze. Bearings are either of leaded bronze, tin alloys, phosphor-bronze or aluminum alloy. The door handles and allied fittings may be of zinc alloys plated with copper, nickel, or chromium; the radiator tank is made from brass, the body trimmings, bumper, etc., are made from high purity aluminum, chrome plated steel or hybrid materials; spark plugs are made from nickel alloy containing manganese, chromium-silicon and based in ceramics; the contact breaker terminals are made from tungsten. A number of other materials including plastics, rubber, glass, hybrids, composites, etc., are on the motor vehicle. The fabrication and joining of most of these materials for the vehicle have been made possible by advances in machine tool technology, materials protection, machine design, robotics, etc (all of which are themselves, materials technology driven).

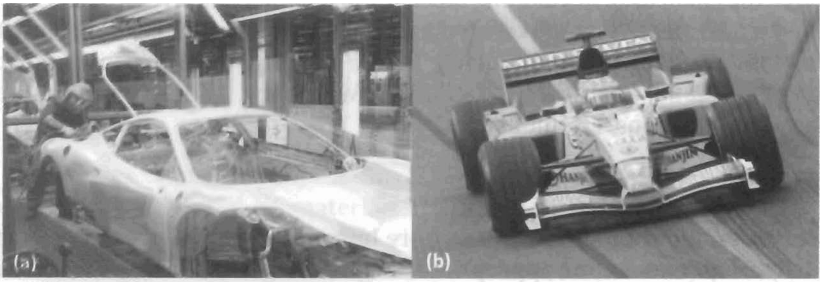


Figure 11: (a) A Ferrari Model Car with Reinforced Aluminum Alloy for the Main Body and Fender (Mukasyan (2014)). (b) The bodywork of a Formula-1 Race-car Made of Carbon-Fibre Composite (Poch, 2007).

The shipping industry has evolved over time due to man's ability to develop materials capable of withstanding high stresses in highly corrosive and sometimes cryogenic media conditions and to build state-of-the-art hulls, high-horsepower engines, rotors, navigation systems, decks and holdings, etc.

However, the advent of mechanical flights is regarded as one of the spectacular impacts engineering in general and materials technology in particular, has made in the society since the first successful passenger flights were made early in the 20th century. The progress has been spectacular and its consequences have altered the course of history (Afonja, 2002).

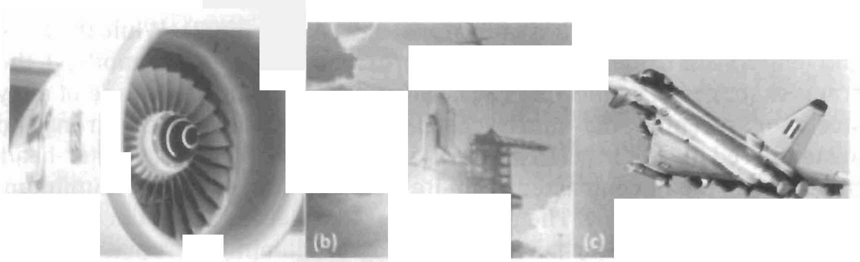


Figure 12: (a) Turbo Jet Engine, Incorporating Metals, Super-alloys; (b) Space Shuttle, Incorporating Super-alloys, CMCs, CFRPs, etc.; (c) Supersonic Fighter Jet, Incorporating Hybrids, CMCs, CFRP, Super-alloys, super-plastics, etc. (www.uc3m.es: Chapter_1_1.pdf)

Interestingly, materials for the design and construction of airplanes have evolved from wood and wire to tubular steel and light alloy strips. Today, appropriate and optimal materials have been developed, including strong but low density alloys, superalloys, CMCs, polymers, etc., capable of withstanding high combined stresses and temperatures. The development in the 1960s of the first generations of supersonic aircrafts capable of travelling at twice the speed of sound and the introduction of Concord Supersonic aircraft series a couple of decades later that remarkably reduced the London-New York flight time from 6 to just about 2 hours, was a major development in the aviation industry. Indeed, this was a far cry from the 1903-05 entrant of the Wright brothers which had an unladen weight of only 275 kg (with the engine alone accounting for 30 % of the weight), and which could only cover a maximum distance of only 15 km and flight duration of only 38 minutes, carrying only one passenger. By contrast, the Boeing 747 built in 1983 had an unladen weight of about 400 tonnes (including fuel), the engine being only 5 % by weight. It could fly non-stop for over 13-15 hours covering a maximum distance of over 11,000 km, while carrying 550 passengers and tons of luggage. It must be mentioned here that these major developments and breakthrough inventions which have now turned the world into a global village, were anchored and made possible by the spectacular invention of the turbo-jet engine by F. Whittle of the UK in 1932. The design required special high strength, high temperature resistant materials – superalloys, CMCs, etc., capable of withstanding temperatures of up to 2000 K and special titanium alloys which have up to 40 % strength-to-weight ratio advantage over steel, and developed to achieve the high-power-to-weight ratio required to meet such outstanding requirements.

A hypersonic aircraft capable of flying at 21 times the speed of sound, while significantly reducing the flight time from New York to Tokyo, Japan to just under 2 hours, is currently being developed. The aircraft will need special high-strength aluminum alloys, metal/non-metal composites, rubbers, and superplastics, etc., for the body structure while the required engine materials can be said to be literally out of this world! Based on these technologies, designers are already working on commercial airliners capable of carrying up to 1000 passengers, arriving at destinations in record time.

Mr. Vice-Chancellor sir, the fact is that these phenomenal developments have all been materials driven. I have mentioned earlier the issue of the materials revolution that has made space exploration such a success over the years. In fact, the first visit of man to the moon in 1960 would have been impossible without the development of appropriate materials which could withstand enormous stresses and extreme temperatures to which the shuttle was subjected, the astronauts clothing and kits, and the numerous electronic and telecommunication gadgets used on the trip. And yet, the work is still ongoing to develop in space, super-high-purity high-performance materials, which currently cannot be produced under normal gravitational conditions (Afonja, 2002).

5.3.10 Materials in Building Construction

Modern developments in the building construction industry have always been materials driven. Sky-scraper buildings, dome-structures, long-span-over-heads, bridges, large stadia, etc., became possible only when appropriate high-strength reinforcing steels (rebars) became available. In particular, the development of aluminum and ceramic corrosion resistant roofing sheets and tiles has completely revolutionized the building industry. We now have extruded anodized and other specially treated aluminum profiles for windows and doors; ceramic, asbestos and rubber floor tiles, insulation and acoustic materials and hybrid composites for other aspects of buildings.

The building industry is also going the way of nano-technology! We now have an emerging area of commercial interest called "nano-Architecture". This is an emerging technology being created by a CalTech scientist that is developing nanostructured materials that are strong but at the same time flexible, light and which can be precisely tailored for specific applications (Fonseca and Newton (2015)). One such materials is the novel 'Digital Ceramycs' (Figure 13 (a)), an E-screen fabric which is versatile and energy efficient and can be used for advanced energy efficient applications and architecture (Templeton et al, 2014). There are glass paints that can keep structures cool; precisely the materials we need in the tropics! Two other novel commercial products are worth mentioning here: DEKTON is one material product adapting nature's own metamorphic stone that takes thousands of years of heat and pressure to form. But with DEKTON (Figure 13 (b)) this forming process is cut down to just four hours through a proprietary technique called particle sintering, in which the raw nano-materials are compacted using a 25,000-ton press. The resulting product is an 'ultra-compact-surface', that is resistant to impact, scratching and abrasion. It is thermal shock resistant as a result of frequent freezes and thaws and has high colour stability due to its UV- and water-resistant properties. A similar product to DEKTON is Fibrirock, which on the other hand, mimics natural basalt rock but it is produced as continuous weavable fibres that are fire-resistant. It is a potential replacement to toxic asbestos fibres in reinforced composites.

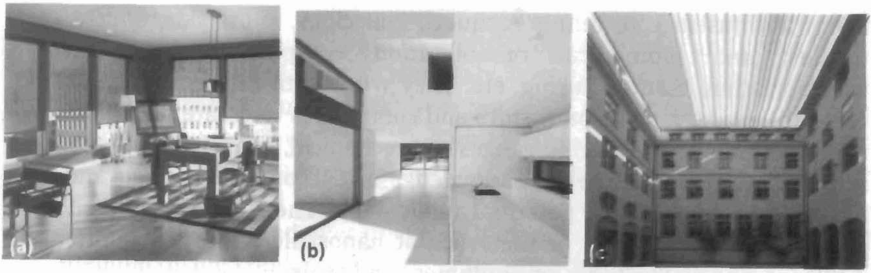


Figure 13: (a) Digital Ceramycs, an E-screen fabric; (b) DEKTON, with an Ultra Compact Super-hard Surface; (c) TENARA Non-degradable Fabric (Templeton et al, 2014).

The second product is the TENARA Fabric (Figure 13 (c)) by SEFAR Architecture. This is a special fabric woven from the extremely inert polytetrafluoroethylene (PTFE), which captures and filter light without making a space gloomy, folds and drapes beautifully and lasts for years; even outdoors. It's ability to stand up to damaging UV rays, acid rain, salt water, and other environmental hazards, make it an ideal choice for luminous tensioned fabric structures, retractable roofs, air-inflated sculptures, etc. Also, since TENARA does not degrade during its useful service life, it can be reprocessed and used in other applications (Templeton, et al 2014).

6. The Roles of Stakeholders in Engineering Materials Development and Innovation

Mr Vice Chancellor sir, my distinguished audience, let me make this assertion at this point: that in a general sense, all scientists and engineers are materials professionals – being connected one way or the other with the handling, processing, management and/or application of materials in their various disciplines and human endeavors! In fact, a confluence of developments in the fields of materials science and engineering, physics, chemistry, biotechnology, medicine, dentistry, pharmacy, electronics, computer technology, mechatronics and advanced manufacturing technology (AMT), non-destructive testing, (NDT), modeling and simulation, tools and signal processing, etc., is contributing to the excitement and fuelling some of the most compelling advances in technology that we are witnessing today. However, the materials scientist/engineer has been the one best suited and indeed has been playing a prime role in harnessing these knowledge-based developments in order to produce and make available the requisite optimal engineering materials and products that are driving the achievement of these technological feats. I have discussed extensively above how materials scientists and engineers are involved in extensive research and development, processing, testing and selection of materials used to produce a range of novel components and products; from high-tech computer chips and aircraft wings and fuselage to tennis racquets, golf clubs, snow skis, and to cars, textiles, and biomedical rehabilitation equipment, drug delivery, transportation, manufacturing, etc. They work with refined metals, alloys, ceramics, plastics, semiconductors and composites to create new and novel materials that meet specific ranges of mechanical, electrical and chemical service requirements. They use knowledge-based concepts to select and rank materials for new and/or potential applications. They have been involved in recent extensive studies of materials at nanoscale and even femto-scale regimes using state-of-the-art equipment and tools.

Mr. Vice-Chancellor sir, distinguished ladies and gentlemen, it is clear that the growing demand for smart and advanced materials that support human activities to make life easier, safer and more secure also poses challenges and presents opportunities for new and innovative contributions from the materials science and engineering community. A team at the Massachusetts Institute of Technology (MIT), USA has recently developed a method for quantitatively assessing the role of materials innovation in overall technological development for a couple of specific breakthrough cases in computation and defines the key requirements to use the procedure in a number of other cases. According to Magee (2012), about 2/3 of the total progress in computation over the past 40 years has been due to materials/process innovations. It has also been observed that making reasonably reliable estimates and/or predictions in other functional areas such as energy, storage, information transmission, etc., could be possible only if more attention were paid to the development and collection of technical progress matrices at the level of materials and processes (in the same way Moore's Law has done for information transformation!). In particular, examination of what is known has led to three other key findings: i). Materials/process innovation contributes at least 20 % of the progress in all areas examined; ii). The contribution of materials/process innovation in energy storage are possibly 80 % or higher; and iii). The relative contribution of materials/process innovation to overall technological progress has grown in the past few decades.

Another study by MIT (MIT Technology Review, 2015) has suggested that the journey from a new material to product typically takes one to two decades. That's in a large part because new materials require advanced manufacturing technologies that can take many years to develop. But to reduce this time lag and fast-track the development of new products, the US hopes to cut that time by half by investing over a quarter of a billion dollars in a "***Materials Genome Initiative***" (MGI), aimed at encouraging more efficient use of the computational modeling tools that researchers use to predict the properties of new materials. The initiative which is a part of the White-House's **Advanced Manufacturing Partnership** (AMP), supports open access to these models and databases across the materials' world in the hope of connecting academics with industry earlier in the development process. This special set of modeling, simulation and predictive tools and codes have been successfully used by materials professionals (academics and manufacturers/industrialists) over the years to fast-track the emergence of products, by manipulating data about stringent properties such as melting point, conductivity and/or the way a compound reacts with others to predict whether a material is suitable for a particular application. Although such tools have been used over the years to narrow the problem of differences in manufacturing conditions in the laboratory and industrial scale, but minor differences in manufacturing conditions still exist when scaling up from making grams of a material in 'clean room' conditions, to making it by the ton in industrial scale set-up. It is a well-known fact that today; many advanced materials gain their extra-ordinary properties through molecular or even atomic-scale-structural-precision manipulations, but making them isn't like making, for example, steel by melting metals together in a large vat. The former 'bottom-up' method uses more-stringent control methods, or the atoms (which seem always to have lives of their own) won't do what you want! Thus, minor inconsistencies in say, temperature control, mixing parameters, or some other factors can lead to failure. Furthermore, most techniques used to achieve atomic-scale precision processing in the 'clean room' laboratory can be very difficult to translate to large-scale manufacturing. It is interesting to note here for example, that silicon which is brittle in the bulk state is indeed over x 10^3 times stronger than steel in the nano-regime!

Mr. Vice-Chancellor sir, distinguished ladies and gentlemen, I wish to state here that the Departments of Materials Science and Engineering, Physics and Engineering Physics (Materials Science Option) and the Centre for Energy Research and Development (CERD) at Obafemi Awolowo University, Ile-Ife, have a pioneering contribution to our national engineering materials development efforts (being the first Departments in sub-saharan Africa in training, research and development in materials) and that as of today, OAU has the largest group of materials professionals in any institution or establishment in Nigeria. I wish to humbly say here too that we have special interest in and we have made some modest contributions in the last 30-40 years, through our research and publications in some of these niche areas of materials research and development mentioned above. It was here in OAU that the Nigerian Materials Research Society (Nigerian-MRS) started in 1999, and which later in collaboration with the National Agency for Science and Engineering Infrastructure (NASENI), started the Materials Society of Nigerian (MSN).

6.1 Efforts of National Funding Agencies and Policy Initiators in Materials Development

6.1.1 US Materials Genome Initiative and Advanced Manufacturing Partnership

Brief information about the US government's sponsored Materials Genome Initiative (MGI) and the Advanced Manufacturing Partnership (AMP) has been given above. Both ideas have yielded outstanding outcomes over the years and ensured that the US continues to take the lead in novel materials development and innovations. MGI and AMP have the mandate to coordinate and enforce the strict adherence to R & D standards and code of practice and make sure that required resources are well managed and made available to researchers on competitive basis, from National data banks and funding agencies. Since the primary idea is to foster and enhance research and development information dissemination and sharing, to fast-track sustainable R & D in critical areas of needs, there has been tremendous progress in many fronts and stakeholders are always well rewarded. The idea has yielded new material products and technologies. Other countries in North America, Europe and Asia have since followed suit to establish their own national initiatives and partnerships.

6.1.2 International Technology Roadmap for Semiconductor (ITRS)

Although the ITRS is not a research discovery, but a notable way of organizing research priorities and planning R & D, it is indeed a remarkable global achievement. It sets out goals for innovation, technology needs, and measures for progress that all can sign up to in the fiercely competitive microelectronics industry (Wood, 2008). The effort has achieved giant strides in semiconductor and microelectronics research and developments and continues to extend the frontiers of research in this direction. According to Wood (2008), not only is electronics absolutely critical to our modern world, progress in semiconductor processing and advances in materials science and engineering have gone hand-in-hand for the last six decades and more.

6.1.3 The National Nanotechnology Initiative (NNI)

The NNI which was a US Federal, multi-agency research program in nanoscale science and technology initiated in 2000, has had an immense impact on R & D by cementing the importance and promise of a hitherto nascent, emerging field and establishing it as the most exciting area of research. In particular, nanotechnology simultaneously gained an identity, a vision, and a remarkable level of funding through the NNI (Ashley and Greenemeier, 2013). It was indeed a 'new industrial revolution' powered by systematic control of matter at the nanoscale. The NNI involved a coalition of academia, industry, and a group of agencies, and has been the largest single investor in nanotechnology research in the world. The global nano-related R & D budget was in excess of $12 billion in 2007. Also, the NNI has direct funding access to the US: National Science Foundation (NSF).

The Nigerian version of NNI was launched in 2005 under the platform provided by the US-Africa Materials Institute (USAMI), Africa-Materials Research Society (A-MRS), the National Agency for Science and Engineering Infrastructure (NASENI) and the Materials Science and Engineering Society of Nigeria (MSEN). The Nigerian NNI has made tremendous strides in popularizing nanoscience and technology research in Nigeria through its several activities aimed at fostering high levels of collaborations amongst researchers in Nigeria and the developed world. The Obafemi Awolowo University in August 2012, won the hosting rights for the Centre of Excellence and capacity building in Nanoscience and Technology. OAU is hosting the M.Sc. degree program in Nanoscience and Technology, initiated by NASENI as part of a World Bank STEP-B Project sponsored set of programs in Advanced Manufacturing Technology (AMT). The M.Sc. degree programme in Nanoscience and Technology is to provide relevant multidisciplinary education in this cutting edge area of Nanotechnology and Structured Materials designed to meeting emerging challenges in the areas of science and engineering, especially in energy, electronics, healthcare, agriculture, telecommunications, transport, security and environment. The programme has four areas of specializations for graduates in the programme. These are Nano-medicine, Nano-energy, Nano-genomics and Nanostructured Materials. Obafemi Awolowo University has comparative advantage in resources and personnel, with requisite expertise and orientation in these cutting edge fields, to deliver on the programme's set objectives.

The specific objectives of the programme are to;

- provide relevant multi-disciplinary education in Nanotechnology and Structured Materials designed to meet emerging challenges in the areas of science and engineering, especially in energy, electronics, healthcare, agriculture, telecommunication, transportation, security and environment ;
- equip graduates with the knowledge and problem solving skills and techniques to apply concepts in nanotechnology to solve problems in areas of critical national development;
- encourage graduates to acquire the knowledge and competencies in the application of tools, techniques and

procedures in Nanotechnology to diagnose and treat a wide range of life-threatening diseases ; and

- provide opportunities and create conducive learning environment for graduates to develop an appetite and attitude towards research innovations and creativity in Nanotechnology.

7. Some Major Advanced Manufacturing, Breakthrough Technologies and Novel Materials

In the last fifty years, developments in materials research have yielded novel materials and new techniques that could turn newer materials into products for use in energy, computation, biotechnology and healthcare, telecommunications, space exploration, etc. I highlight below (not in any particular order), a few of these major novel material products and materials driven technologies.

(i). Scanning Probe and Tunneling Microscopes

The invention of the scanning tunneling microscope (STM) in 1986 by Nobel laureates in Physics; Heinrich Röhrer and Gerd Bining is a most remarkable development, coming after the outstanding success of the SEM and TEM. The STM provided a way to probe the local properties and characteristics of a sample directly with nanometer resolution. The development of the STM was quickly followed by that of the atomic force microscope (AFM) for nanoscale characterization and to provide a new access to the nanoscale world of materials, than never before then (Wood, 2008). These and other inventions such as the orientation imaging microscope (OIM), Electron Backscatter Diffraction (EBSD) analysis, and fabrication techniques such as the focused ion beam (FIB) and electrode discharge machining (EDM), etc. have immeasurably increased our R & D abilities at the nanoscale.

(ii). Giant Magnetoresistive Effect

The Giant Magnetoresistive (GMR) effect was discovered in 2007 by Nobel laureates Albert Fert and Peter Grünberg. GMR describes the large change in electrical resistance seen in stacked layers of magnetic and nonmagnetic materials when an external field is altered. A further work by Stuart Parkin and co-workers at IBM Research has enabled the phenomenon to be further explored and put to great effect in the read-heads in hard-disk drives (Wood, 2008). Today, such devices are able to read out the information stored magnetically on a hard-disk through changes in electrical current. The high sensitivity of GMR has influenced our ability to store and retrieve data through magnetic bits on a hard-disk that we continue to witness and improve upon today.

(iii). Lasers, Masers and LEDs

The major development of the semiconductor laser (Light Amplification by Simulated Emission of Radiation) and light emitting diodes (LEDs) in 1962 is still a great materials science and engineering story as they are now the basis of telecommunications, CD and DVD players, laser printers, barcode readers, etc., today. Lasers are in use in navigation, high precision measurements, military guided-weaponry, signal guides, medical surgery, metal-cladding, etc. Microwave Amplification by Simulated Emission of Radiation (Maser) is the sound-microwave equivalent of the laser technology and it is used extensively in telecommunications, seismic, radio, space, etc., research and applications.

(iv). Micro-Electro-Mechanical-Systems (MEMS)

Micro-electro-mechanical-systems (MEMS) are miniature, micrometer-scale devices comprising of integrated (e.g. on a semi-conductor chip) mechanical (micro-levers, gears, valves, switches, springs, deformable membranes, vibrating structures, etc.), electrical/electronic (resistors, capacitors, inductors, etc.) components and computers, designed to work in concert to sense and report on the physical properties of their immediate or local environment; or when signaled to do so, to perform some kind of controlled physical interaction or actuation with their immediate or local environment (MEMSBLOG, 2016). They are deployed in diverse applications, ranging from display technologies to sensor systems to transducers and microswitches, satellite telecommunications, wireless/remote systems and to optical networks. They provide significant cost advantages particularly when batch-produced through parallel fabrication techniques, which may further lead to cost reduction. Some MEMS feature sizes are of the order of the wavelength of light, which makes them attractive for many optical applications. Another advantage includes the 'on-chip' integration of several MEMS and the circuitry (OS) used to control them, allowing further miniaturization.

In visualizing MEMS, Paul McWhorter (2008) of MEMX.COM, asked us to just imagine a machine (Figure 14 (a)) that is so small (like a grain of pollen) that it is imperceptible to the human eye and having thousands of such machines batch fabricated and integrated on a single chip, all at a very low cost. Imagine a world where gravity and inertia are no longer important, but atomic forces and surface science dominate (as in a 'clean-room') and then, imagine a silicon chip with thousands of microscopic mirrors working in unison, enabling an all-optical-network and removing the bottlenecks from the global telecommunications infrastructure.

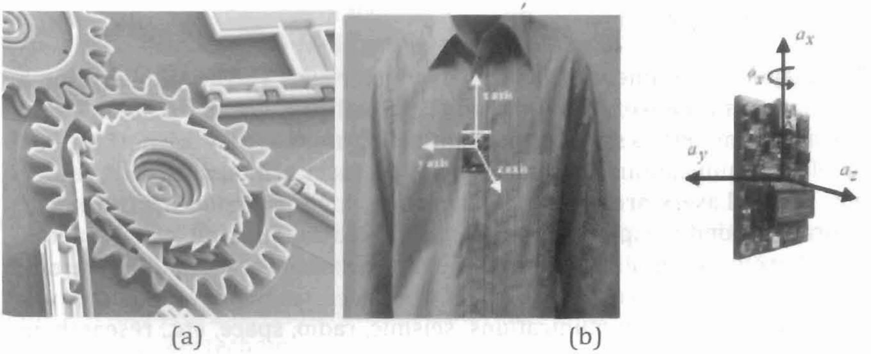


Figure 14: (a) LIGA-Fabricated Integrated MEMS Accelerometer Device (About MEMS.htm); (b) A Tri-axial HMR MEMS Sensor Tagged on a Subject's Chest (Ahmed and Song, 2012).

Then you are now entering the world of an explosive technology known as MEMS – a world of challenge and opportunity where traditional engineering concepts are simply turned upside down, and the realm of the 'possible' is totally redefined. Now think about the almost invisible smart device that senses that your car has been in an accident, and in micro-seconds, triggers the air-bag to envelope and protect you – **MEMS**!

Figure 14 (b) shows a single MEMS accelerometer that can be used to recognize and record human motions using features based on non-parametric clustering method (Ahmed and Song, 2012). With this device, the seemingly unanticipated set of human motions are detected and recognized with significant accuracy. Human motion recognition (HMR) is a current area of research and development due to its potential applications in tracking, personal navigation, health-care, personal life log, surveillance, sports, etc., activities and domains. HMR is mainly monitored via wearable sensors like the body-mounted accelerometer sensor (Figure 14 (b) and/or image-based recognition (cameras). The advantage of the camera aided object motion identification is that multiple subjects can be monitored simultaneously without the need for any additional device. We have seen its use in investigations incorporating CCT video playbacks of terrorist attacks, surveillance and similar activities. But it does suffer from clutter, cluster and environmental effects like; lighting, etc., under different settings.

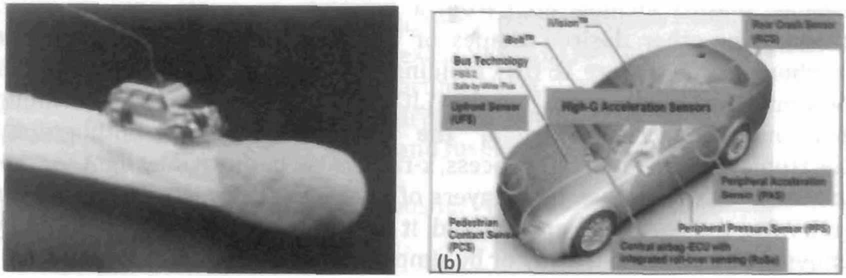


Figure 15: (a) DENSO (MEMS) Micro-car on a Match Stick (Denso Corporation, http://www.denso-int.com); (b) Automotive Application of Micro-electro-mechanical-systems (MEMS) (www.find mems.com/MEMS@ BOSCH, 2010).

However, the body mounted (accelerometer) sensor can be person-specific and independent of environmental conditions. Sensors are miniature and/or compact (some like the 'smart dust' are as small as a pollen grain!), portable and processing data does not require a great deal of resources. The down side of the body-mounted sensor has to do with mainly issues of early battery exhaustion and hence it's malfunctioning, depending on how long the tracking or surveillance, etc., lasts. Today, there are HMR systems that are adaptable, accurate and robust to the dynamic nature of human motions.

As previously stated, MEMS are miniature-sized devices produced using IC batch fabrication technologies. In order to appreciate the size of an integrated MEMS device, we consider the renowned DENSO Micro-car perched on a match-stick (as shown in Figure 15 (a) - (Denso Corporation, http://www.denso-int.com)). The DENSO Micro-Car is a miniature version of Toyota's first passenger car. It was fabricated using MEMS, at 1/1000th the size of the original, it consists of a 0.67 mm magnetic-type working motor and when supplied with 3 V 20 mA of alternating current through a 18 μm copper wire, the engine runs at 600 rpm equivalent to 5-6 mm/s.

Modern high-end vehicles feature up to a hundred different MEMS sensors and allied devices – accelerometers, gyroscopes, inclinometers, pressure and flow sensors, IR sensors (for air quality), micro-scanners (for displays), oscillators and energy scavengers, etc., all making the vehicle safer, more energy efficient and more environmentally and user friendly (Figure 15(b)).

MEMs fabrication technology can be grouped under three main headings; surface micromachining, bulk micromachining and molding (Madou, 2002). In surface micromachining, thin films of metals, alloys, oxides, nitrides, etc., are deposited on a substrate and appropriately patterned, using photolithography, to create micromechanical devices (Figure 16 (a)). Bulk micro-machining is carried out by removing material (e.g. through deep-etching, plasma etching, etc.) from a substrate to create holes, cavities, channels or other desired shapes or features to be integrated into the machine system (Figure 16 (b)). Molding involves filling a mold to create the desired component parts. In the LIGA (Lithographie, Galvanoformung, Abformung), an acronym for the German words for lithography, electroplating and molding) process, x-ray, visible or ultraviolet light sources are used to fully expose thick layers of photosensitive material (Figure 16 (c)). After the part has been molded, it may be removed from the mold by either etching the mold away or by simply peeling it away for reuse.

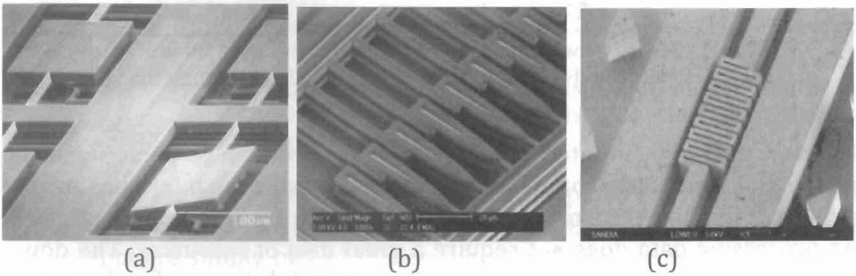


Figure 16: (a) Titanium mirrors bulk micromachined using deep etching of a titanium substrate; (b) An electrostatic comb drive fabricated using SUMMiT, a surface-micromachining foundry process; (c) An extremely low-loss coplanar waveguide fabricated using LIGA (Introduction to Microelectromechanical Systems (MEMS) _Compliant Mechanisms.htm).

Commercial applications of MEMS include, microsensors (e.g. acceloremeters for the deployment of air-bags), pressure sensors for biomedical applications and micro-actuators (e.g. for moving arrays of mirrors in projection systems, etc.). Nanoenergetics (the integration of reactive nanomaterials into MEMS) is a relatively new technological area where the parlance: "***Making Great Things From Small Things***" is literally true. There are also BioMEMS for heart, lungs, etc., repairs. There are a lot of novel MEMS devices for military warfare and intelligence gathering applications. They have only become smarter, robust and high-precision enabled.

(v). Carbon Fiber reinforced Plastics (CFRPs)

The CFRPs are light but extremely strong composite materials that have found extensive applications in aviation/aerospace, transportation, packaging, civil engineering, and sporting, etc., industries. They are now used extensively in Formula 1 cars, armor and special wind turbines rotor blades. They are also known as 'continuous carbon fibre organic-matrix composites', they bond extremely stiff, high-strength carbon fibers into a polymer matrix, resulting in a composite that is also exceptionally tough and light weight. Today, pole vaulting field-sport is made much easier using pole of this material, resulting in outstanding performances by athletes that only have to depend on their superior vaulting techniques to excel. Tennis racquets, golf clubs and racing bikes are a few other examples of CFRP sporting items that have completely revolutionized the sporting world. The Boeing 787, similar, latter and more advanced models of airplanes are also known to use CFRP composites extensively in their wings and fuselage.

(vi). Quantum Tunneling Composite (QTC) and Thermo-Colour Sheet/Device

The novel QTC while in an unstressed state is a near-perfect insulator; however, any form of deformation (or pressure) on the material produces a proportional change in electrical conduction, with sufficient pressure yielding metallic levels of conductivity (Cunningham, 2013). From basic Physics point of view, an electron cannot pass through insulation barrier. On the contrary, from Quantum Physics theory, a wave of electrons can pass through (by tunneling) an insulator. This explains the QTC operation. It can be used as a superb switching and sensing material (Figure 17 (a)). QTC is made from conductive filler particles combined typically with silicone elastomeric rubber binder.

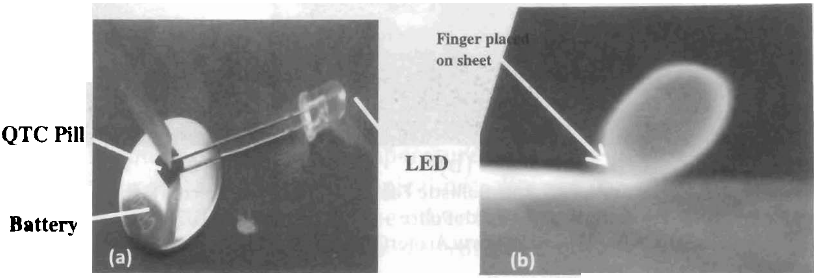


Figure 17: (a) Quantum Tunneling Composite (QTC); (b) Thermo-Colour Sheet (http://www.galwayec.ie)

The Thermo-colour Sheet (Figure 17 (b)) and the device based on this technology are another set of examples of novel smart materials. The sheet is normally a self adhesive sheet, film or tapes whose colour changes according to the temperature (whose measurement can be read out digitally). It is used extensively, in heat-warning patches and novelty advertising products (http://www.galwayec.ie). Also, in some novel thermometers (e.g. optical and radiation pyrometers), the thermocolour component/device, incorporating a digital recorder/analyzer, allows the temperature of heating units like rotary furnaces, extended or large heating panels or spans, etc., to be evaluated without getting too close to the object of interest.

(vii). KEVLAR® and NOMEX®

Kevlar is a wonder material made from plastic polymer strong enough to stop bullets and knives, and it is five times stronger than steel on an equal weight basis (weight-to-strength ratio). It has found applications in making boats and bowstrings, windsurfing sails, reinforcements in tyres, brake pads, armour vests, cars and aircraft bodies. Kevlar is a proprietary material patented and made exclusively by DuPont™ Chemical Company, USA. Nomex is a similar protective material to Kevlar and they are both examples of chemicals called 'synthetic aromatic polyamides or aramids for short. Kevlar is made from a chemical called poly-para-phenylene terephth-alamide – (reduced to Kevlar for short). They are further refined by dissolving the threads and spinning them into regular fibres. The woven Kevlar forms a strong and flexible material. Layers are combined with alternate layers of resin, resulting in a rigid material. With nanotechnology, Kevlar have been further processed to be over 20 times stronger than steel.


(a) (b) (c)

Figure 18: (a) Kevlar 29 Style 745 Anti-Ballistic Fabric (www.ArmorCo.com); (b) Kevlar Anti-Ballistic Helmet (@OrlandoPolice – FoxNews.com, 2016)); (c) Kevlar Anti-Ballistic Panel NIJ IIIA (www.ArmorCo.com).

Figure 18: (a) shows the Kevlar 29 style 745 anti-ballistic fabric for use for personnel soft body armor and antiballistic vests won by police and other law-enforcement agencies. Other Kevlar based products include racing helmets, anti-ballistic helmets (Figure 18 (b)), spall and car-door panels (Figure 18 (c)), anti-ballistic blankets and hard military armor products. I should mention here too that the anti-ballistic helmet (Figure 18 (b)) won by a SWAT-OPD security officer during the ill-fated June 12, 2016 terrorist-mass shooting attack on the Pulse Night-Club in Orlando, Florida, USA, spectacularly saved his life (FoxNews.com, 2016). The Kevlar anti-ballistic Panel NIJ IIIA (Figure 18 (c)) is a typical bullet/missile resistant panel that can be used in conjunction with vehicle door 'skin' or metal of similar weight and thickness or used alone. These flexible Kevlar anti-ballistic panels are 'Thermo Activated'; meaning that a heat-gun can be used to bend the panels into shape and they will retain that shape after the process. They are also available with a rubber coating that allows them to remain flexible although

they may lose their 'Thermo Activated' properties, but gain in weather resistance and flexibility. The WBT-1 Electric Scissors (www.ArmorCo.com) is a typical light weight, portable and convenient battery powered scissors that can cut multiple layers of Kevlar fabric and fiberglass with ease. They have two sets of high hardened tungsten steel blades for durability, fast and accurate cuts and longer life that compared favorably with conventional electric shears.

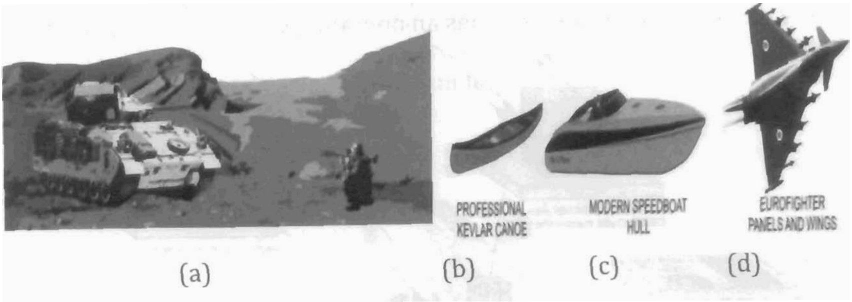


Figure 19: (a) US Army's 'Bradley Fighting Vehicle' with Kevlar® 29 Armor Panels; (b) Professional Kevlar® 49 Canoe; (c) Modern Speedboat with Kevlar® 49 Hull; and (d) EuroFighter Jet with Kevlar® 49 Panels and Wings (Ryan (2001) – TYPES OF KEVLAR.htm).

Kevlar® 29 is the ideal body armor material for lightweight military-type personnel carriers such as the renowned US Army's 'Bradley Fighting Vehicle' (Figure 19 (a)). This material was selected for its armor because of its lightweight, non-flammable and ability to withstand attack from RPGs. It offers protection from high temperature or intense-heat sources (fire bombs, Molotov cocktails, etc) and tropical hot climatic conditions (Ryan (2001) – TYPES OF KEVLAR.htm). On the other hand, Kevlar® 49 is used extensively for specialist canoe and boat body-work and hall, respectively (Figures 19 (b) and (c)), and in aerospace industry, because of its lightweight, ability to withstand a considerable amount of force (torque, etc), tensile/torsion stresses and impact. The boat is relatively lightweight, faster and easier to maneuver in water and more fuel efficient. The Eurofighter jet (Figure 19 (d)) is a relatively lighter, force/impact-resistant, faster, more versatile, fuel efficient stealth attack jet than its rivals due to the use of Kevlar® 49 as the armor-material in its manufacture ((Ryan (2001) – TYPES OF KEVLAR.htm).

(viii). Vision: "Smart Dust" – Integrated MEMS Sensors and Transmitters

About a decade ago the internet went viral with the rider: "Vision Smart Dust" – Peeping Particle: Even the Dust has Eyes! This was in reference to a novel wireless-sensor-network micro-device (Figure 20) with on-board integrated MEMS sensors and transmitters that has numerous exciting applications in virtually all fields of science and engineering, including health care, industry, military, security, environmental science, geology, agriculture and social studies (Ilyas and Mahgoub, 2005). In particular, the combination with MEMS-based sensors and actuators is intriguing because it permits manipulation of the environment in an unprecedented manner. The "smart Dust" has in-built software that collects and analyzes data for multi-hub messaging, time synchronization, sensor data acquisition and filtering, collaborative signal processing, position estimate update and query response. It virtually has a life of its own! It is essentially a cubic mm in volume and contains sensors, a microprocessor, RF communication and a battery or solar cell for power. It has an operating system called "Tiny OS".

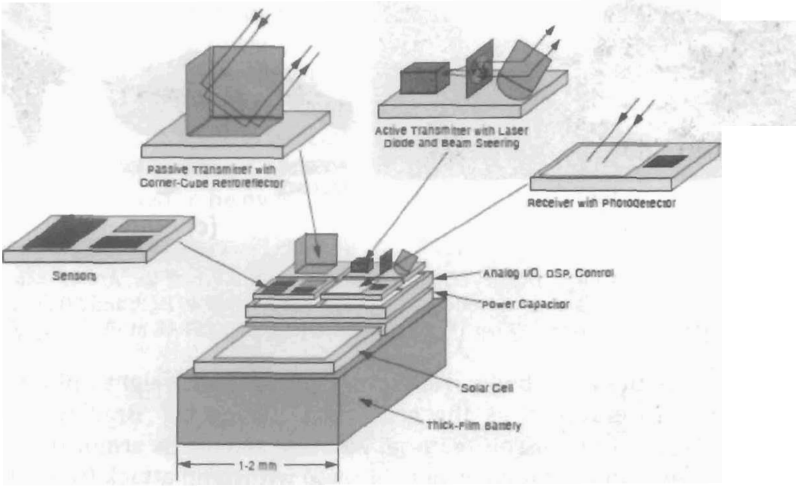


Figure 20: Smart dust mote, containing microfabricated sensors, optical receiver, passive and active optical transmitters, signal-processing, control circuitry and power sources (Ilyas and Mahgoub, 2005).

The "Smart Dust" research has been enabled by the rapid convergence of three key materials-driven technologies: digital circuitry, wireless communications and micro-electro-mechanical-systems (MEMS). Recent advances have led to a remarkable reduction in size, power consumption and cost. Modern "Smart Dust" is small enough to remain suspended in air, buoyed by air currents, sensing and communication for hours or days on end. This is actually where the term; "Vision Smart Dust": Peeping Particle; "even the dust has eyes", took its name and mode of operation in military intelligence work, came from.

(ix). Fuel Cells Technology – Based on Electrochemistry and not on Combustion!

Hydrogen is a versatile energy carrier that can be used to power nearly every end use energy need. The fuel cell (actually a battery) is an energy conversion system that can efficiently capture and use the inherent power in hydrogen to produce 'super-clean' electrical energy and other useful by-products. Stationary fuel cells can be used for back-up power, power for remote locations, distributed power generation and co-generation (in which excess heat released during electricity generation is used for other applications).

Fuel cells can power almost any portable application that essentially uses batteries, from hand-held devices to portable generators (fcth2-fuel cell_factsheet.pdf, (2010)). It can also power vehicles - cars, buses, trucks, marine vessels, etc. Hydrogen is expected to play a particularly important role in the future, by replacing petroleum for our vehicles.

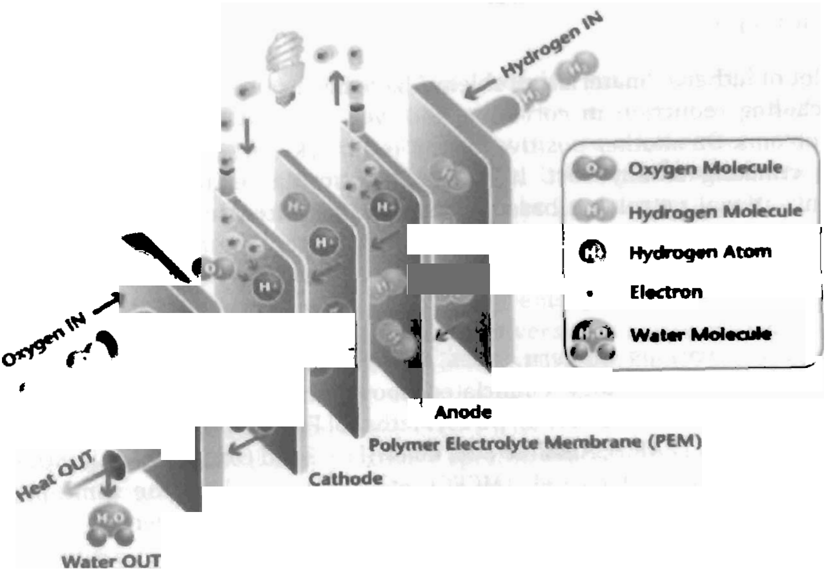


Figure 21: Fuel cells directly convert the chemical energy in hydrogen to electricity, with pure water and potentially useful heat as the only byproducts. Hydrogen-powered fuel cells are not only pollution-free, but also can have more than two times the efficiency of traditional combustion technologies (fcth2-fuel cell_factsheet.pdf, (2010)).

Fuel cells directly convert the chemical energy in hydrogen to electricity with 'pure water' and potentially useful heat as the only by-products. In fact while conventional combustion-based power plants typically generate electricity at efficiencies of 33-35 %, fuel cell systems can generate electricity at over 60 % efficiency (with cogeneration expected to increase the efficiency), operating quietly, with fewer moving parts, and are well suited to a variety of applications.

As shown in Figure 21, a single fuel cell consists of an electrolyte sandwiched between two electrodes, an anode and a cathode. Appropriate bipolar plates on either side of the cell assist in distributing gases and serve as current collectors. Typically, a polymer-electrolyte membrane (PEM) allows hydrogen gas flow through channels to the anode, where a catalyst causes the hydrogen molecules to separate into protons and electrons. However, the PEM allows only the protons to pass through it to the other side of the cell; while the electrons follow an external circuit to the cathode. The result is electricity that can be used to do work. It should be noted that at the other side of the cell, air flows through channels to the cathode, reacting with the returning electrons and the hydrogen to form 'pure water' (an exothermic process) and the release of useful heat which can be used as auxiliary source of heating, etc.

A lot of hitherto 'materials problems' have been solved in fuel cell systems, including reduction in corrosion and wear, and electrolyte management problems. On another positive note, it is a quick start-up system, requiring no cranking of any sort. It has high performance and efficiency over conventional petroleum based systems. It has increased tolerance to fuel impurities. It is a good source of ozonized water – pure water (not poor water, please!). It has better fuel flexibility with a variety of catalysts that can be used.

There are various modern types of fuel cells (all based on the same fundamental technology enunciated above); including: Proton Exchange Membrane Fuel Cell (PFMFC), Direct Methanol Fuel Cell (DMFC), Phosphoric Acid Fuel Cell (PAFC), Alkaline Fuel Cell (AFC), Solid Oxide Fuel Cell (SOFC), Molten Carbonate Fuel Cell (MCFC), etc. They all follow the same basic technological design and are all materials technologically driven.

(x). Materials for Li – Ion Batteries

The advent of high energy density Li ion batteries has completely revolutionized laptop, cellular phone, photography, movie industries, etc., of our time. Li ion batteries required the development of novel electrode materials that satisfy quite a number of requirements. The cathode requires a lightweight compact framework structure with free volume in between to allow a large amount of Li ions to be inserted and extracted reversibly with high mobility. Today, 3-D framework structures are in use, resulting in environmentally benign, high-energy density batteries.

(xi). Carbon Nanoscale Structures (Nano-particles, tubes, belts and wires, graphenes, fullerenes, etc.)

In the last 1-2 decades, materials scientists and engineers have made giant strides in advanced manufacturing technology, computing, telecommunication, electronics, etc., since the advent of novel carbon-based structures and devices. The remarkable, unique and phenomenally promising properties of these nanoscale carbon structures have placed them in a class of their own. Carbon nanotubes essentially act as internal structural supports, scaffolds and frameworks as well as active component parts in telecommunication and allied devices. A lot of R & D efforts are still being channeled to sort out critical issues concerning their cost-effective synthesis, purification, large-scale production and assembly into viable devices, research tools, etc., in order to yield more uniform nanostructures preferably with isotropic or same properties in preferred directions. Recent advances in materials R & D, design, modeling and manufacturing have opened up new frontiers, effectively moving product and component design down to materials design issues.

In particular, graphene has been described as a wonder, super-material that is a one-atom thick layer of carbon with remarkable record breaking properties (Science News, 2014). It has the ability to absorb EM radiation – energy from across the radio frequency spectrum. It has led to super-fast internet and allied services and has the potential to be used to provide secure wireless connections and improve the efficiency of communication devices and the internet itself. It has the potential to revolutionize many areas from electronics to transport, warfare, medicine and energy. An international research team led by Prof. Geoff Nash from the University of Exeter, England, including Dr. Sergey Mikhaelov (University of Augsburg, Germany) and Prof. Jerome Faist (ETH Zurich) has made a remarkable discovery in graphene research (Nash et al, 2015). They engineered a new but remarkable hybrid structure or meta-material that possesses specific characteristics that are not found in natural materials. The researchers combined nanoribbons of graphene, in which electrons are able to oscillate backwards and forwards, together with a type of antenna called a 'split ring' resonator, to produce a system which strongly interacts with electromagnetic radiation. The new structure can be used as a type of optical switch to interrupt and turn on and off, a beam of light very quickly. This is expected to be a good basis for a range of future technologically important components and devices.

Researchers have now shown that electrons in graphene move like molecules in liquid water, while electrical currents in graphene form 'whirlpools', just like water does when a stream is being diverted. These whirlpools can be detected in resistance measurements (Science News, 2016). Other graphene based products include graphene aerogel or elastic foam (one of the world lightest materials!), that can be used for fast oil-spill cleanup. Thus with carbon nanostructures like graphene, the future is now!

(xii). Metamaterials

The discovery at the beginning of the new millennium of materials with negative refractive indexes, suggesting that light or at least microwave, can be bent the 'wrong-way' on entering such material, based on Snell's Law, was a remarkable phenomenon. Thus, Veselago's prediction in the 1960s that materials can simultaneously have both negative permeability and permittivity and as such can also have a negative refractive index was confirmed. This has led to the understanding that a metamaterial in the hue of an artificial structure of repeated micro-sized elements, wires, etc., can be designed to have specific pre-determined properties not found in nature (Wood, 2008). This wire structures have been engineered to generate a negative electrical response at gigahertz frequencies, while split-ring structures can generate a negative magnetic response. Metamaterials derive their properties as much from their internal structures as from their chemical composition. Thus, by adding such structure chemistry as an ingredient can greatly increase the range of resulting properties in this class of novel materials. For instance, just imagine the type of lenses and dc response that can be gotten from this set of novel materials; with frequency possibility in the visible range and downwards. A negative refractive index could be used to construct a 'perfect lens' that can have a resolution unlimited by fundamental physics, of the design, but also of issues of manufacturing. Today, light weight lenses for radar waves have been manufactured using metamaterials and a new approach to subwavelength imaging is now in the realm of possibility!

(xiii). Google's Contact Lenses (Monitoring Blood Sugar Levels!) and Cancer Detecting Pill

Materials technology is always moving, and it touches every aspect of our lives (Larson, 2014). Each year, we see more and more of the reality that hitherto only existed in science fiction come to life. One of such latest novel material inventions is the Google contact lens (Figure 22 (a)). Google is taking their wearable technology ambitions even further with a smart contact lens - but it might not be quite what you think. It's not Google Glass plastered onto your eye. No! But instead of sending you Google+ notifications, its integrated MEMS-based transmitters are used for an entirely different end goal: monitoring diabetics' tears for glucose. Google lens are being developed by Google X, the offshoot of the high-Tech giant that handles their most ambitious and risky projects such as glass and self-driving cars. These lenses see Google moving further into wearable technologies and crossing over into healthcare technology (Larson, 2014).

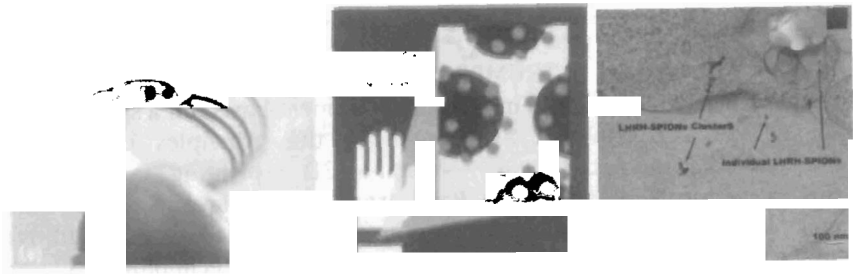


Figure 22: Google's (a) Contact Lens for Monitoring Diabetes; (b) Cancer Detecting Pill (Larsen, 2014); (c) TEM Micrograph of Breast Cancer Cells from a Female Mouse-Injected with LHRH-SPION Nanoparticles with Both Individual Particles and Particle Clusters Distributed in the Cell (Meng *et al*, 2009).

The other latest notable Google futuristic nanomaterials' entry into the world of healthcare in 2014 is its new cancer-detecting pill (Larson, 2014). The pill (Figure 22 (b)) contains magnetic nanoparticles that attach themselves cancerous molecules that may or may not be flowing through the patient bloodstream. The pill would then actually be able to notify the patient on his/her wearable device whenever it has accomplished its cancer purging. Even though it's still years from hitting the market, it's one of those game-changing technologies that only Google has the money, intuition, and ambition to create. I am very much aware that researchers led by Professor W. O. Soboyejo (Princeton University, Princeton, NJ, USA), have made significant contribution in this area of cancer detection and purging (Leuschner *et al* (2005); Meng, *et al* (2009); Oni *et al* (2014)). Meng *et al* (2009) has shown how superparamagnetic iron oxide nanoparticles (SPIONs) conjugated to luteinizing hormone releasing hormone (LHRH); i.e. LHRH-SPIONs can be used to target breast cancer cells (Figure 22 (c)). The particles have also been shown to act as contact enhancement agents during the magnetic resonance imaging of breast cancer xenografts.

(xiv). Electric Ink

The Electric Ink has been described as a quantum-electronic magic that can make strange but useful semiconductors that are insulators on the inside and conductors on the outside (surface). However, the bulk of the material acts as an insulator that blocks electron flow while the surface; a good metal-like conductor, allows electrons to travel freely at almost the speed of light, unaffected by impurities that normally hinder electron motion through materials (Ashley and Greenemeier, (2013). Such inks are now used in making printed electronic materials used in display screens, sensors and batteries.

(xv). Laser Metal Fusion (LMF) and Laser Metal Deposition (LMD)

According to engineers in TRUMPF Ditzingen, Germany, the LMF and LMD novel techniques and the accompanying equipment based on a special laser CAM equipment/technique, are based on the principles of additive manufacturing adapted for metal 3D printing technology (Additive_metal_parts.htm, 2015). Parts are generated, layer by layer, from metal powders that are melted using laser. It is expected that additive manufacturing will not only supplement production technologies in the future, but will also exert a formative influence on them.

(xvi). Flexible 3-D Printing Materials

The TPU-92A-1 is the world's first wonder 3-D printed flexible and fully functional material having high tear resistance, high resistance to dynamic loading and high abrasive resistance. It offers excellent durable elasticity and a 'snappy response' (Hopperton, 2013).

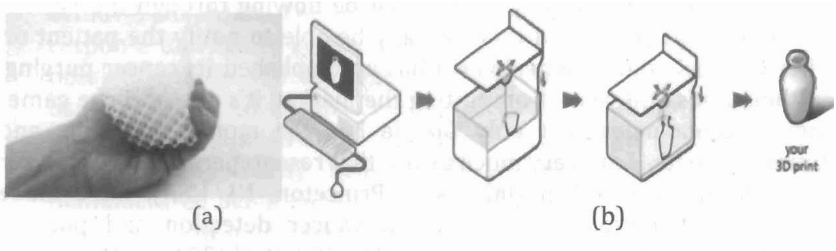


Figure 23: (a) TPU-92A-1 Ultra-Flexible material; (b) 3-D Printing Technique (Palsenbarg, 2014)

The TPU-92A-1 (Figure 23 (a)) is ideal for highly flexible and abrasion-resistant parts in a wide range of applications such as seal and gaskets, complex tubes, hoses and manifolds, elastic lightweight structures, fashion industry products (shoes, bags, etc, components), cushioning and shock absorption and rapid prototyping of elastic components (Palsenbarg, 2014). It is a thermoplastic polyurethane derived from a Shore A92 rubber-like material and constructed from off-white, very fine granular powder through 3-D Printing (Figure 23 (b)). Note that the "1" stands for the fact that it is the first member of a family of such novel material.

(xvii). Tyres That Repair Themselves

This innovation of self-healing in rubber was first reported by scientists from the Leibnitz Institute of Polymer Research, Leibnitz, Germany. It is made of a non-vulcanized tyre-grade rubber that heals itself and could potentially withstand long-term pressure of driving (Austin-Morgan, 2015).

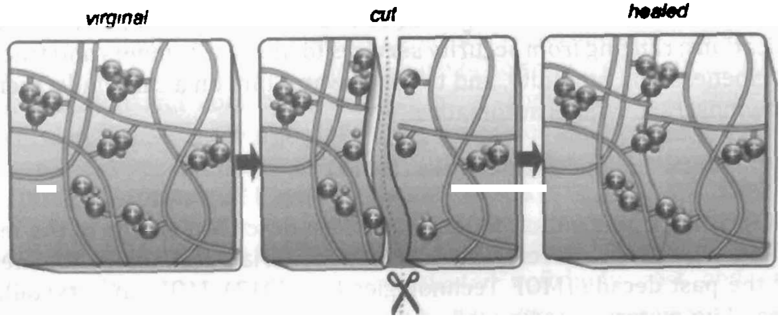


Figure 24: A Schematic Illustration of Tyre Rubber being 'Healed' after being Cut or Pierced (Das et al (2015).

Figure 24 illustrates the healing process of a tyre rubber after being cut, pierced or punctured. The tyre simply knits itself back together after damage (Das et al (2015). The novel material is made using a chemical process that avoids vulcanization altogether but it is based on the modification of commercial rubber into a durable, elastic material that can 'heal' or 'fix' itself over time. Testing showed a cut in the material healed at room temperature and heating to 100 °C for the first 10 minutes accelerated the repair process. And after eight days, the rubber could withstand a stress of ~ 754 psi. The product could be further strengthened by adding reinforcing agents such as sulphur or carbon black (Austin-Morgan, 2015).

(xviii). Super-Absorbient Material Soaks Up Oil Spills

Materials scientists from Drexel and Deakin Universities in Australia have manufactured and tested a new material made of a boron nitride nanosheet that can absorb up to 33 times its weight in oil and organic solvents – a trait that could make it an important technology for quickly mitigating the costly accidents of oil spillage. The material literally absorbs the oil like a sponge and it is a significant advancement in oil spill remediation technology (Science News, 2015).

(xix). Sensor-Sensing Presence or Absence of Objects

Materials scientists have created a novel way of sensing presence or absence of objects in real space; an improvement over existing methods. For instance, entering a room or a gentle clap can trigger the lights to come on, etc. You may have also seen something like this in toilets when you wish to dry your hands, it triggers the auto-self flushing after using the toilet or a door opens when someone approaches. In the latest technique, almost any solid object - such as a potted plant – can be turned into a sensor by careful monitoring of its capacitance (Eureka, 2014). The trick in the new technique is to ensure that small capacitance changes are not swamped by huge background 'noise' levels. The technique is appropriate for almost infinite range of security, measurement and automated system control tasks. There are now so many applications; ranging from security services to medical scanners and tracers, fruit ripeness, soil humidity, and to sense water film on a car windscreen to start windscreen wipers automatically.

(xx). Metal-Organic Frameworks (MOFs)

Metal-organic frameworks (MOFs) have been described as one of the most exciting, high profile developments in nanomaterials technology to emerge over the past decade (MOF Technologies Ltd, 2012). MOFs are crystalline, sponge-like materials composed of two major components, namely; metal ions and organic molecules known as linkers. However, the choice of the metal and linker is known to have significant effects on both the resulting structure and properties of the particular MOF. MOFs have broad industrial applications because of their two key attributes: their extremely large surface areas (but with very low bulk volume, with most of the material being free-space – making them extremely lightweight) and the flexibility with which their structures can be varied. The incredibly high surface area means that MOFs are very good at storing gases. They are also particularly very robust, with exceptionally high mechanical and thermal stabilities.

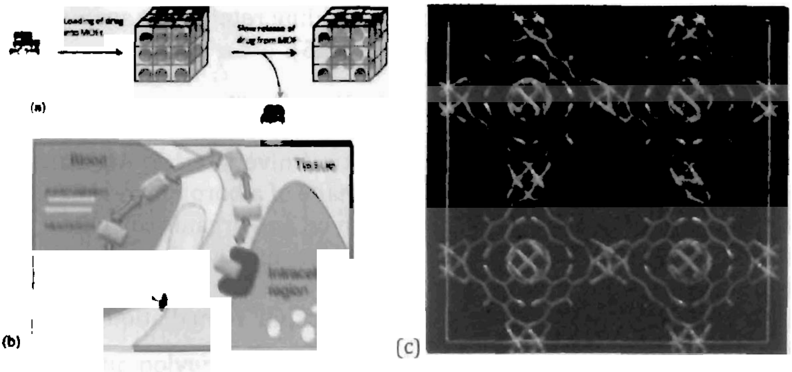


Figure 25: (a) Generalized scheme for the use of MOFs as drug delivery vehicles; (b) In vivo conditions involved in the slow release of drugs (Keskin and Kizilel (2011); (c) The structure of the MOF HKUST-1 (green: copper; red: oxygen; black: carbon; white: hydrogen) that enables stress-induced chemical detection when a thin layer is integrated on a microcantilever surface. Note that in this view, the exchangeable axial coordination sites on the Cu (II) ions are unoccupied (Allendorf and Hesketh, 2016).

In particular, the tailorably nano-porosity and ultrahigh surface areas of MOFs mean that they can be used to filter and separate gases; an extremely important industrial process. Their unique properties afford entirely new ways to manipulate, store and react to a wide variety of substances, which has lead to the rapid development of new applications in areas such as pharmaceuticals, medical imaging, detection and sensing applications, as appropriately illustrated in Figures 25 (a) – (c)) (Keskin and Kizilel (2011); Allendoff and Hesketh (2016)). MOFs have been shown to be suitable for the encapsulation and controlled delivery of a large number of therapeutic molecules, including several challenging antitumor and antiretroviral drugs.

(xxi) Bulletproof and Impact Resistant Glasses

There are amazing new tough glass-based materials that are being used in high-security system such as sophisticated soft-body vest and amour protection units for personnel carriers, submarines, ships and aircrafts. The basic idea is to dissipate the bullet, missile or hammer's energy and so resist motion, penetration or impact. The normal glass offers little or no protection against these items. According to the Griffith's theorem when a bullet, say, strikes a pane of ordinary glass, the bullet's energy pushes against the glass, making fractures to radiate out from the point of impact in 'lines weakness' and making it to shatter into huge shards. The bullet keeps going forward with hardly a loss of momentum. However, modern bulletproof or impact resistant glass is very different. It is made essentially from alternate layers of polycarbonate, acrylic or polyurethane (a tough type of plastic, sandwiched in between pieces of toughened glass to form laminates. Thus, when a bullet, missile or hammer strikes such impact resistant glass, its energy (and/or cracks) spreads out radially through the laminates and is absorbed and the cracks arrested. Although the 'energy-absorbing' glass panes may break, the plastic layered component stops them flying apart. These are the type of armored doors banks should be using in Nigeria!

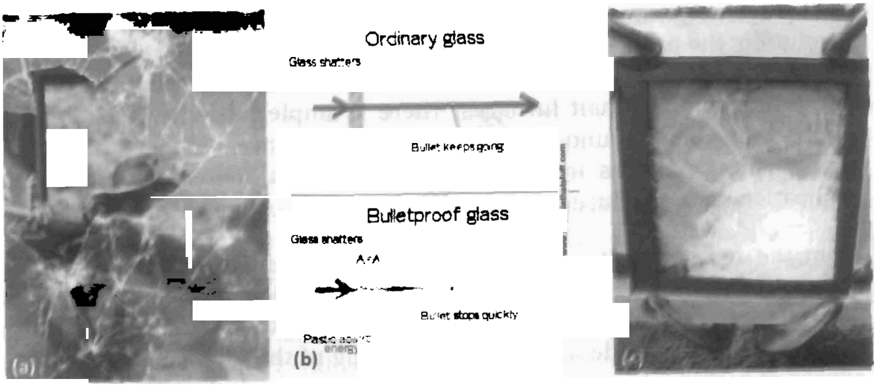


Figure 26: Left: Ordinary glass shatters and does nothing to stop the passage of a speeding bullet (Middle-Top: Schematic Illustration). Right: This bulletproof armor withstood the impact of a .30 caliber armor-piercing bullet fired from 23 m (25 yards) away using a Russian M-44 sniper rifle; (Middle-Bottom). (Woodford, 2016).

Mr. Vice Chancellor sir, Nigeria has had a rather chequered history and experience in engineering materials and hence technological development. There is ample evidence to show that the Benin, Ile-Ife and Igbo-ukwu bronze/brass castings and practice, which date back to thousands of years, were sophisticated and world renowned. Archeological excavation of Acheulian tools in Jos Plateau and Nok to the North-east of Nigeria, have been dated several years, BC. The Nok Culture people were known to have employed a fully evolved iron technology, smelting iron from presumably limonite and hematite pebbles, magnetic sand, ferruginous sandstone and ferricrete, all of which are abundant in many parts of Nigeria. In fact there is ample evidence that Africa played a prominent role in the early Iron Age, with some of the most sophisticated smelting furnaces dating back to this period being found in Togo and Nigeria. These were shaft furnaces of superior design compared with the dome furnace types used in many other regions active in iron making during the same period (Hupfield, 1899). Excavations in Taruga (about 55 km South-east of present day; Abuja) led to the discovery of thirteen iron smelting furnaces, iron artifacts and founding products dated to around early 400 BC; the oldest so far discovered in Africa (Tylecote, 1970). Other excavations made in Bussa (Borgu) in 1966 to 1968 (Fagg, 1969) and 1975 led to the discovery of about 2000 objects that showed that there were also agricultural communities using iron tools before the end of the first millennium BC.

According to Afonja (1989), one unique feature of the iron making culture in the African region was that, whereas other regions transformed to the Roman Iron Age and were subsequently swept along by the Industrial Revolution, the early Iron Age persisted in Africa. Iron products were being produced in Oyo, Western Nigeria as late as 1910, and using traditional forced-draught low shaft furnaces. There is ample evidence that the Oyo practitioners had sound knowledge of the prime role of carbon in strengthening iron, as iron with different carbon contents for different application were produced.

From the foregoing, it is clear that Nigeria sustained the Iron founding culture for about 2,500 years during which a high degree of skill and perfection were achieved. It is generally believed that the Iron Culture in Nigeria began to recede around the beginning of the 20th century with the advent of high quality iron and steel products of the Industrial Revolution that were brought into the country by the colonialists and the subsequent ready availability of scrap iron and steel (as feedstock) which could be hot-forged to make farm, machine and war implements (Afonja, 1989).

But all of the above are way back in the distant past! From the last six to seven decades or thereabouts, Nigeria's efforts in engineering materials and indeed in technological development have been marred by a series of catalogues of errors and poorly thought-out and implemented acts of 'political correctness', but economically, operationally and materially very wrong decisions and development plans. Thus, unlike the "Asian Tigers" that started on the "Technology-Road" about the same period with Nigeria, we have little or nothing to show for our journey, thus far. As Afonja (2009) opined, backed by historical development information presented above, the problem is not in our stars but in us! Also, as I had mentioned earlier, Nigeria is richly blessed with abundant deposits of mineral/materials resources – crude oil, natural gas, tin, columbite, tantalite, iron ore, feldspar, galena, limestone, marble, uranium, gold, gem stones and other highly-priced solid minerals. In particular, the crude oil deposit is acclaimed as the 7th largest in the world, while newer deposits are being discovered on a regular basis. Also, the natural gas deposits are even more extensive, even as gas flaring is now being significantly minimized. The revenue from oil and gas amounts to over 89 % of Nigeria's foreign exchange earnings; most of which is used to import a myriad of raw materials and finished products, without adding much value to these resources (Afonja, 2002, 2009). It is therefore ironical to note that despite this level of revenue and resources, Nigeria still remains in the lower rungs; as the 13th poorest nation in the world, with a very low human development index (UNDP, 2001). Indeed, today, local engineering materials production as well as the contribution from the manufacturing sector are virtually non-existent or too low to be referred to as 'modest'. So, what went wrong?

Mr. Vice chancellor sir, the abysmal state of engineering materials development in Nigeria is certainly one talking point that I have been opportune to interact on and contribute to for quite a number of years. I have been involved in several interactive sessions, round-table engineering materials policy initiatives and other fora that were led by Prof. A. A. Afonja, the late Prof, O. O. Adewoye and a host of other very eminent personalities at home and abroad, who are resource persons on this issue. In particular, Prof. Afonja has written and spoken a lot on this issue, on which we have been brainstorming even until very recently. I am therefore going to highlight some of our well considered but multi-faceted reasons why Nigeria's engineering materials and indeed technological development have been a '**basket-case**' and I will attempt to proffer a few required steps to be taken for solution towards remedying the situation.

Available records show that so far, virtually all efforts by Government to set up a sustainable engineering materials base for infrastructure, the manufacturing industry and allied sectors and for fast-tracking Nigeria's technological development, have met with little success (Afonja, 2002, 2009).

For example, two of the three paper mills have folded up and the third is almost comatose; unable to meet any major delivery target in the last two and a half decades. The textile, hydes and skin and allied industries are only living on past glories! The petrochemical plant at Eleme, which should produce the required raw materials for the polymer industry, is virtually unable to meet local supply requirements. The Aluminum Plant at Ikot-Abasi is not doing much nowadays, while the tin industry like for most other solid minerals, is comatose. The ceramic industry is under-developed and needed major life-line, even from the rather low-level private sector participation, which in itself, has been virtually non-existent. For now the cement industry seems to be the only one delivering to meet local consumption and export. However, this last singular seemingly positive case is still dented by the non-availability of low-cost, locally produced standard structural/reinforcement (rebars) steels needed for the building construction industry. The result has been the prevalence of collapsed buildings here and there, often blamed on substandard structural reinforcements and poor detailing!

The iron and steel industry has been touted since the late 1970s and early 1980s as the industry that was to leap-frog Nigeria into a superb manufacturing-industrial enclave, in the hue of Japan and South Korea. But today, four of the five steel plants have completely collapsed with the fifth one; Ajaokuta Steel Company (ASC), having never really taken-off. In fact, the present imbroglio in the ASC was only recently brought to the fore, with the recent reported information from the Hon. Minister for Solid Minerals Development, to the effect that the Federal Government will not touch ASC until all legal issues pertaining to the revamping of the project are resolved (@dailypostngr, May 26, 2016). There has been a pending but debilitating court case between the Federal Government of Nigeria and a foreign core investor; Global Infrastructure Holdings Limited (GIHL), which claims that ASC was concessionaired to it in 2004. The Hon. Minister was quoted as saying: "For us, Ajaokuta is priority but nobody is going to touch Ajaokuta in the International Investment terrain until it become unencumbered". "Ajaokuta was concessioned off in 2004 by President Obasanjo, and in 2008, President President Umaru Yar'Adua came and revoked it. It is being contested now that the revocation allegedly did not take into account that the concession had not expired. The GIHL took Nigerian Government to the Arbitration Court in the United Kingdom. Up till last week (i.e. 2nd week of May, 2016), the Attorney-General and I (the Hon. Minister) still met with the mediator who came all the way from London". The Hon. Minister explained further that "six Countries had recently approached the Nigerian government to revive Ajaokuta within 24 months, adding that the President was interested in partnering with one of the Countries", but: "we have to resolve the legal issue on ground because Ajaokuta has become a collective **shame** to Nigerians"! Indeed, that is what it has become!

A recent unconfirmed report says that the matter has now been resolved out of court but the settlement involves the return of the National Iron Ore Mining Company (NIOMCO) at Itapke plus a whooping sum of US$250 million to GIHL. Would this have happened to a private firm?

Perhaps, because it wasn't even well planned for, there is no single industry in Nigeria that is capable of making automotive, rail, water, oil and gas, and industrial quality cast components or even bolts and nuts. The machine tools industry in Nigeria has been rudderless!

Mr. Vice-Chancellor sir, I have more to say shortly about the Nigerian Iron and Steel project in general and the Ajaokuta Steel Company (ASC), in particular; as a special case-study. This was one industry that was touted in the 1980s as Nigeria's bedrock and launching pad to a full-blown industrial revolution, but which seems to have fallen short of all expectations and has even now become a monumental embarrassment to the Nation, that is, re-echoing the words of the Hon. Minister for Solid Minerals Development.

However, Nigeria can be said to be fortunate to have an abundance of well-trained and articulate set of experts in virtually all fields of endeavor, most of them trained in ivy-league institutions abroad. There are probably more trained Nigerian materials professionals abroad than in Nigeria, with most of them making significant contributions in leading industries, universities and research institutes and in consulting; a situation aptly referred to as "brain-drain". To buttress this assertion, I wish to re-echo the report given by Afonja (2002) about a visit made by former US President; Bill Clinton, towards the end of his tenure to a leading aerospace research establishment in the US, prior to his last official visit to Nigeria. Clinton was shown a novel composite material developed by the agency. The material had superior properties compared with any existing material available for the application of interest. He was said to have been pleasantly surprised when the staff that developed the item was introduced to him: he is a Nigerian! Again, only a few weeks ago, our own dear Prof. Deji Akinwande (of the Department of Electrical and Computer Engineering, and the Education Director, NASCENT-NSF-NERC Center, Texas Materials Institute (TMI), the University of Texas at Austin, USA), was at the White House to receive the US Presidential Early Career Award for Scientists and Engineers (PECASE) from President Barack Obama (White House Press Release, 2016). Prof. Akinwande and his team worked on 'Silicene' (a silicon analogue of graphene) and their research article was the most cited 2015 Nature Nanotechnology Paper in 2015. The Silicene device breakthrough was selected among the Top 100 Science stories by Discover – The Year in Science. Akinwande had earlier worked on the first flexible phosphorene transistor and radio demodulator, published in Nano Letters and highlighted in the NPR, IEEE, UTexas, MIT Tech Review and over 50 international news media. There are a number of other Nigerians who are products of our local institutions, perhaps for their first degrees, who are now prominent in cutting edge research and development; in metallurgy, electronic materials, nanomaterials, laser and maser technology, fibre-optics, polymer technology, engineering ceramics, etc. I know of Prof. Winston Oluwole Soboyejo of Princeton Materials Institute (PMI) and long-time Coordinator, Undergraduate Programs in Princeton University, Princeton NJ, USA, whom I have had the good fortune to collaborate with in MEMS research and development. He is an expert in MEMS, BioMEMS, flexible electronics, NanoMedicine and drug-delivery systems. Also, our local universities are full of well-trained academics and materials professionals, trained in top universities at home and abroad ('brain-gain'!), some of whom, perhaps, are yet to consider emigrating to the more developed countries for 'greener pastures'. OAU has the largest hub of Materials professionals in any institution or agency in Nigeria. The bulk of this set of materials professionals are members of Materials Science and Engineering Society of Nigeria (MSEN) – formally Materials Society of Nigeria (MSN). The MSEN has since the early 2000s been collaborating with the Nigerian Materials Research Society (Nigerian-MRS), the African Materials Research Society (A-MRS) and the umbrella body; International Materials Research Society (I-MRS) to organize the Annual Nigerian Materials Congress (NIMACON), to extend the frontiers of knowledge in materials science and engineering. NIMACON provides a forum for Nigerian materials professionals to interact and continually appraise the National materials policy, R & D, practice, continuous professional development (CPD), etc., and present well researched papers on all aspects of materials science and engineering. NIMACON has been holding every year since 2002. It was in one of such meetings in 2003 that the idea of the Nigerian Nanotechnology Initiative (NNI) was born. OAU, Ile-Ife, the birth place of MSEN and indeed the place where you have the largest presence of materials professionals in any institution or agency in Nigeria, won the hosting rights for the postgraduate programme in NanoScience and Technology after a very competitive bid at the August 2012 Workshop on Curriculum Development for NASENI STEP-B World Bank Project for the Centres of Excellence in Advanced Materials and Manufacturing Technology (CoE-AMMT) in Minna, Niger State, Nigeria. The program has been duly approved by the Senate of this great University. However, it is yet to fully take off!

It is therefore ironical to observe that Nigeria which can be said to be so rich in mineral, material and human capital/resources is also so poor in all development indices! What is the matter then?

Mr. Vice Chancellor sir, I wish to state here that I belong to a group of stakeholders and resource persons on engineering materials technology, ably led by my mentor and erudite scholar; Prof. A. A. Afonja that has been brainstorming over the years, on the onerous problems of Nigeria's engineering materials development in general and the Iron and Steel Project, in particular. A lot of technical papers and presentations have been published by Prof. Afonja and members of our group on these issues. But I wish to briefly attempt here to highlight some critical factors and talking points that we consider to be Nigeria's "catalogue of errors" and/or misplaced priorities, which may have culminated in the rather abysmal state of this important national project. Although, I have chosen here to evaluate Nigeria's steel development project, I humbly believe that the same set of 'issues' beset to a large extent, other national projects like the aluminum, oil and gas, petrochemical, etc., industries. I highlight this catalogue of errors and other issues (not in any particular order) with respect to the Nigerian Iron and steel project in general and the Ajaokuta Steel Company, in particular, below:

(i) Nigeria's Penchant for Taking "Politically-Correct" but Ill-considered Technological Development Decisions

It has been observed that most nations that have developed strong iron and steel industries, including Japan and India, started with a small plant and gradually expanded. India commissioned the British to build their first plant, the Germans built the second plant some years after, the Russians built their third plant, while they built the fourth plant themselves, having gradually acquired the technology (with a hands-on experience of their own on how to handle a couple of shut-ins problems, etc.).

- However, Nigeria decided to start two large-scale plants at the same time in the mid- 1970s. Both the Ajaokuta and Delta Steel plants were designed to produce the same product mix – structural steel which is mainly for construction, and not manufacturing. This situation was said to have arisen because two rival groups in the same Federal Ministry could not agree on which technology to choose from two options, so the Ministry decided to recommend both options which translated to Ajaokuta (Blast Furnace Route) and Delta Steel Company, Aladja (Direct-Reduction Route).

- Delta Steel Company (DSC) was designed to have four (4) melting furnaces to feed four rolling mills but the military government at the time decided to move three of the rolling mills inland to Osogbo, Jos and Katsina to "promote the spread of development", ignoring informed opinion and warning that billets could never be transported to the inland mills from Delta Steel Company (DSC) Aladja, since there is no rail network in the Delta region. DSC ended up with surplus capacity for producing billets while the three inland rolling mills were starved to death of billets. Thus the 'politically correct' decision to move three out of four rolling mills from DSC, Aladja early in the life of the Nigerian steel industry, to the inland set-ups at Katsina, Jos, and Osogbo indeed sealed the fate of the rolling mills from inception, and which further exacerbated their problems when DSC collapsed. It is a well-known advantage in major plant design that most if not all ancillary or mini-plants are to be located for economic and managerial reasons, near the parent plant; to be connected by appropriate railway lines, land and seaports (i.e. close to the 'source'!)! And what were the 'collateral' results of this monumental error of judgment? We got seriously damaged roads, hold-ups, everywhere the heavy-duty trucks conveying cold billets take to the rather distant inland mills, with the attendant frequent fatal accidents. Then the billets have to be reheated (at high energy-cost) at the mills before being rolled; a sure drain on electricity supply from the national grid.

The technology for Ajaokuta should never have been adopted since it requires over a million tons of coking coal and high grade iron ore a year, all of which would have to be imported. The blast furnace cannot tolerate shortage of feed materials! Once started/fired, it must run 24/7 for four to five years; non-stop. It is not surprising that after over four decades of ASC's existence; only the light section rolling mill of the plant has ever been operated, and only for a few weeks in the early 1980s, fed with imported billets. But today, almost all the major operational units have been dismantled and the equipment sold out at cheap rates. And to also think that the particular form of blast furnace route for ASC is the first of its kind anywhere in the world, and it was not even in operation in the erstwhile USSR that was promoting it! YOU CANNOT BE SEEN TO BE MAKING PROGRESS WHEN YOU ARE ON THE WRONG ROAD!

As in other major national projects, the iron and steel development project was being run as a government parastatal! But globally, the adage that says "Government has no business in business" is sacrosanct, but not here in Nigeria! For example, the British steel industry, which was the bedrock of Britain's industrial revolution, has remained privatized and stable for decades. In Nigeria's case, the fact that all the plants were managed directly from a Federal ministry by non-technical ministers (senior and junior (minister of state?)) and directors was another major reason for failure. Practically all the operating plants from inception had full complement of staff even when none of the plants ever went beyond 15 % capacity utilization before they closed down. One of the plants had nearly 5000 workers even when the plant was producing at 10-15 % capacity. The only issue that still makes the news today in relation to the plants, is the staff agitation through long-drawn-out labour battles with management on their allowances! Of course, no private enterprise in the developed world worth its salt can ever do such and survive. The role of governments in developed climes is to provide the enabling environment for private sector businesses to thrive. This is not the case in Nigeria!

To date there is no local manufacture of the type of steel required for manufacturing (machinable steel, flatsheets, alloy steels, stainless steels, alloy steel castings, etc.). In fact, automobile manufacture is a very fertile medium for the acquisition and domestication of technology. However, there must be a well-established and empowered small-medium-scale industrial sector to produce the over two thousand components. Most countries that have successfully established an auto industry in recent times (India, South Korea, South Africa, etc.) started with an assembly plant, facilitated local production of most of the components, then moved on to establish more plants. They are all leading exporters of automobiles today. However, Nigeria established **six (6)** assembly plants at the same time with no effective plan in place to grow the local component manufacturing sector. Inevitably, local input remained rudimentary until all the assembly plants closed down. THE NIGERIAN STEEL DEVELOPMENT SITUATION WAS LIKE "PUTTING THE CART BEFORE THE HORSE"! The steel plants were set-up without planning adequately for the next-level-end-users; the primary product utilizers such as the automobile, railway, industrial machinery and spare-parts, etc, industries. AS THEY SAY; "YOU CANNOT BE FASTER THAN YOUR DRIVER! Unless you want to crash through the windscreen!

State of Infrastructure: Another major problem with the steel industry is the poor state of infrastructure in the country: electric power, road-rail-networks, water supply, etc. Even when generating plants are available, the gas or diesel required to run them is another hassle. It is also expected that plants requiring uninterrupted water supply (for cooling, treatment, barge transport, etc.), should be located near large body of water like the ocean, etc. Most of the iron and steel plants, and in particular, the ASC's blast furnace are meant to be run for long furnace operating periods without shut-downs due to power failure, non-availability of required raw-materials, etc., although there may be a few controlled 'shut-ins' of one or two sub-units for a few minutes, to effect minor maintenance, adjustments, etc.

(ii) Government Import-Export Policy Issues

Another issue in 'political correctness' is the open door importation policy of Government which works against industrialization in general and manufacturing in particular. This policy has signed the death warrant of the iron and steel industry in particular, since the imported products are considerably cheaper than locally produced ones. The Nigerian Cable Plc and MICOM Cable Limited know this very well. It is the norm in most developing economies to decide to severely restrict imports of certain goods/items. The case of India is a prime example. In the late 1940s, while lunching India's first Development Plan, the then Prime Minister; Mahatma Ghandi made his renowned declaration: "What we can make, we will use, what we cannot make, we will do without"! They stuck to this policy over the ensuing years, and they are the better for it now. Today, both India and Japan (which also adopted a similar policy after World War II), to a large extent, produce virtually every component of the vehicles they produce (out sourcing none), industrial machinery and spare parts, most of which are exported for foreign exchange earnings. However, Nigeria was exporting crude - raw materials without adding value to it, prior to export, only to import finished products at an exorbitant value. Of course, the local industries barely survived this.

Again, before our very eyes, lorry-loads of critical scrap metal and allied products are being collected all over the country, melted, cast into billets and shipped out by Chinese and Indian firms to their countries, without adding any value to it, here. The Delta Steel Company and perhaps, the Nigerian Foundry Limited are expected to use these ready high-alloy-content scraps in their plants! This is another cheap source of charge materials that is being lost daily to the unscrupulous activities of foreigners and their Nigerian collaborators. Obviously, government policy on this matter is very wrong, because this bad practice is still going on.

(iii) Funding

This is a major problem everywhere. Business loans at reasonable interest rates cannot even be guaranteed by Government! The fact is the issue of funding like all aspects of project planning, budgeting and implementation in Nigeria, is beset with corruption. We now hear of budget 'padding', kick-backs, etc! In the end, the required funding earmarked for vital national projects will not be available as and when due to execute them.

(iv) Is the Problem that of Poor Planning or Implementation or Both?

In the last four-five decades, every Nigerian Government whether military or civilian has articulated one development or sustenance plan or the other for the iron and steel industry in Nigeria. However, none of them has succeeded in effecting any meaningful progress in this critical national project. According to Afonja (1986), the perennial lack of a well articulated, coherent, coordinated and realistic government policy has had an even more devastating effect on our industrial development. This is clear from the few National Development Plans that have been developed so far. In all most all cases, projects were merely listed, usually with the assistance of foreign experts (in the hue of the International Monetary Fund (IMF), etc.), without due consideration of the country's capacity and capability. Again, the steel plants required over 40% electric power from the dwindling national grid for adequate operation, a further example of the rather deficient and uncoordinated planning which is evident in virtually every aspect of the nation's industrialization policy and implementation of same. It is not surprising that many projects that were eventually embarked upon were either still-born or crippled.

Thus, if one considers that execution (to an appreciable degree) is part of effective planning, then it can be concluded that successive governments lacked proper planning capability. My humble take is that every one of these governments has always sought to be "politically correct"; as they say. They jettison sound economic and technological development advice for lame political aggrandizement and patronage. We have seen this played out in the petrochemical, iron and steel, automobile, power sector, etc, national projects.

(v) Poor University- Industry Cooperation

There is virtually no University-Industry cooperation in research and development in Nigeria. It is a well established fact that most countries that have developed exploited this vital asset to the fullest. There is no visible progress on the decision to fast track training of postgraduate students and personnel by the first generation universities in Nigeria. The local content initiative also appears to be visible only through media hype than in reality.

(vi) Nigeria's Preferred Strategy of Importing Technology Turnkeys/Wholesale

This unwholesome policy which was put in place to support import substitution, ensures that businesses are established mostly by foreigners and with little or no technology acquisition or transfer. This is the same route preferred by most African countries. The pertinent question is: why do we clamor for the 'transfer of technology' from the developed nations? This can't happen voluntarily, since that would be a sure way of putting the developed world out of business! I should mention here too that Japan for several years, stuck to their "copy and adapt/re-engineer" technological policy rather than any unfavorable or near-impossible voluntary technology transfer. After a while, Japan spent most of her now acquired expertise and capacity re-engineering and developing these inventions and eventually started selling the products to the original inventors. Today, Japan is ahead in robotics and she is even 'giving it back' to the UK to teach their young kids programming in early 'hands-on' demonstration and practice classes, at a huge cost. South Korea, Malaysia, Singapore and even reclusive China, are doing the same thing to Japan now. But unfortunately, Nigeria was one of the first 'developing' countries to sign the extant 'copyright' laws!

(vii) Nigeria's Fixation with Grandiose Steel Projects

Mr. Vice Chancellor sir, from the foregoing, it is clear that despite the huge investments, the steel industry in particular and virtually all national development projects in general, have made no significant impact on Nigeria's industrial development. None of the five now moribund steel plants was producing the vital grades and forms of steel that are required for manufacturing, resulting in dire problems such as product mismatch between plants, wastages, etc. For example, as mentioned above, DSC was producing billets which it cannot transport to the far-flung inland satellite rolling mills located in Jos, Katsina and Osogbo, that were planned to reheat and re-roll it to finished primary products. Worse still, ASC's only one operating light steel rolling section, was also importing its required billets because it required a different sized one from the surplus being produced by DSC. What is this then?

It is rather ironic that Nigeria is still fixated about a steel development project that has gone awry, at a time the developed world is moving away from traditional steel-based manufacturing to the development and use of more versatile and cost-effective modern engineering materials, and even less expensive ferrous technologies and products; like ductile and austempered ductile irons (DI/ADI). It is therefore my humble submission that it is time to cut our losses and stop further wastage of our hard earned resources in ASC and DSC.

The Way Forward?

As I had mentioned earlier, ductile (DI) and austempered (ADI) ductile iron castings have proven to be the cost-effective ferrous materials of choice and/or potential alternatives to other competing but expensive steel and aluminum materials and manufacturing processes, with either an improvement in service performance or lower production cost or both. The outstanding growth in the use of ductile iron castings in engineering applications including those in which the casting properties are critical to lower energy utilization, safe operations and in safety related components such as automobile steering knuckles and brake calipers, gears, pinions, valves, pumps, etc., and building construction materials, etc., has occurred because of the tremendous improvement in production capabilities of the castings, resulting in quality consistency and freedom from imperfections, obtained through stringent microstructure control. Thus the increased demand for improved performance output and fuel efficiencies, decreasing noise and pollution and reduced costs in automobiles, marine vessels and other dynamic-load bearing systems have led to the development of novel cast iron materials with superior strength to weight ratios (than comparable high grade alloy steels), and that add up to more strength for less expense. Nigerian researchers have the requisite expertise and comparative advantage in DI-ADI production and applications.

Mr. Vice Chancellor sir, based on the fore-going, I wish to humbly suggest that our moribund steel plants should be resuscitated through a cost-effective redesigning of existing facilities and injection of few cost-effective new ones, for DI and ADI production and development. The DI-ADI process will need a lot of the iron and steel scraps that are presently being lost through surreptitious export by unscrupulous foreign companies in Nigeria. Nigeria may do well to add value to the iron ore, coal and limestone products from deposits in the country, through beneficiation for local use and export to earn needed foreign exchange to run the redesigned plants. There is therefore the need to reappraise the ASC, DSC, etc., projects in this direction.

9. My Odyssey through the World of Engineering Materials and Humble Contribution to Knowledge in Teaching and Research

Mr Vice chancellor sir, I must mention here and with sincere gratitude, that my odyssey into and through the interesting but challenging world of engineering materials was shaped here in Ile-Ife, way back in the late 1970s, early and mid-1980s by Profs. A. A. Afonja, O. O. Adewoye (Late), E. O. B. Ajayi, O. Ajaja, J. B. Aladekomo, S. O. Ogunade, M. A. Salau (Late), J. A. Ali, UNILAG's C. M. Kamma (Late), O. Adepoju (Late) and S. Balogun, etc., and further honed later by Profs. H. Blumenauer, O. -K. Prietzel, E. Schick, I. Wagner, U. Wendt (all of IWW/TUM, Germany), W. O. Soboyejo (AME/PMI/PRISM, Princeton, USA) and a host of others of my lecturers and senior professional colleagues who have imparted positively on my training and career advancement over the years. I did not have any qualms about choosing Engineering Physics (Materials Science Option) as my course of study and University of Ife (as it was then), in 1978. I had a role model in a close family friend; Abel Obabueki, who was going into his penultimate year in the course and University. He lived just two streets away from my family house in Benin City and we meet to discuss every time he was home on holidays. On this particular holiday, I just asked him a few questions, and I can recall that he gave me a brief talk about engineering physics being about harnessing the best aspects of engineering and applied physics for research and innovation into materials, devices, etc, and nuclear engineering. He showed me a set of brochures from Stanford University, McMaster and a few others. I was smitten! I picked the JAMB (the very first set then in Nigeria) form on a Friday, completed it over that weekend and submitted it the following Monday, because I did not want to change my mind and I'd assured Abel that I would not. I came into the course in 1978 and in 1979, I had a dream meeting with this enigmatic lecturer; O. O. Adewoye. I had just registered for EBH 201- Properties of Engineering Materials, a core course for all engineering and physical science students that was to be handled by him. "O O" had a personal collection of two vital resource books on the course; Van Vlack (Elements of Engineering Materials) and L. Barrett (Materials Science and Engineering). I told Abel to assist me and my friend Abraham Ogwu (now a Professor of Materials Science and Engineering; University of South West Scotland, UK) to get us these two books from Prof. Adewoye, for a very short time. Abel told us to go and see "O O" ourselves! After some hesitation, we went to "O O" in his private office cum laboratory. We introduced ourselves and told him we wanted to have a quick 'look' at these two books. To our great surprise, he got up from behind his desk, went to the shelf, pulled out the two books and handed them to us. We signed the register and as we turned to leave the outer office, he called us back and asked us to sit down and relax. He gave us such an inspiring lecture on materials science and how it was going to impart on modern technology in the nearest future that we both made up our minds to remain in the course, and not seek to transfer to say Chemical, Mechanical, Electronic and Electrical Engineering. More importantly, we both henceforth had access to coming to the outer office/mini-library to study in the evenings and listen to new 'materials gist' from "OO". We became members of his junior 'inner cycle' academic family. It was that simple and a rare privilege!

I was among a lucky set of students in my class when after our third year, we were selected to undergo the new four-year Engineering Physics Programme which meant in essence, that we'd graduate with our immediate seniors in the erstwhile five-year programme. That is, the erstwhile five-year programme was being collapsed to four in our set and yet we were required to fulfill all science and engineering courses' requirements for graduation! We could cope only because Profs. Adewoye, Ajayi, Salau, etc., were there for us. We had nine (9) of us (five (5) in Materials Science and four (4) in Nuclear Engineering options)) that made the 'graduation list'. Prof. Adewoye was our course adviser throughout and he kept us on our toes. I was again lucky to do my final year project with Prof. Adewoye and I got the best thesis prize for materials science in my graduating class. It was a turning point in my forays in materials training and research. I worked on the characterization of some clay minerals in my B.Sc. thesis. In a way, I cut my teeth in experimental techniques under Prof. Adewoye's tutelage and I have not slacked since! Interestingly, six (6) of the Nine (9) of us that graduated in 1981/82 Engineering Physics set are now professors, one (1) is an MD/CEO of a foremost Telecoms Company and President; Association of Telecommunication Companies of Nigeria, while the last two are top engineers/managers in Shell Development and Production Company of Nigeria, who have now moved to Canada, as expatriates.

I came back to Ife for my masters in 1985 and again sought to work with Prof. Adewoye, who was this time the Head of Department of Metallurgical and Materials Engineering. This time I worked on corrosion and corrosion fatigue of mild steels in some corrosive media. The study had the main objective of providing data for the design and development of local steel-based components and machinery operating under combined fluctuating loads and corrosive media, such as in food processing plants and in particular, cassava milling machines. For this work, I carried out a mathematical modeling of the fatigue failure criterion and testing procedure and validated the model with experimental data from the work. A few papers were published from this work, and I became a full member of the Corrosion Research, Monitoring and Prevention (CRMP) program group at the Department of Materials Science and Engineering, Obafemi Awolowo University, which was headed by Professor Adewoye. I also had the opportunity of working on a unique Wear Testing Machine designed and developed by the group. We calibrated and standardized the equipment to study wear and tribology issues in locally produced engineering materials. We also studied the pack carburization/case-hardening phenomena in mild steels using cassava wastes and other materials, with a view to producing case-hardened set of steel components for food processing machines. We published a series of papers in these areas of research in reputable international journals. I have also collaborated with some other researchers mentored by Prof. Adewoye to extend the frontiers of knowledge on corrosion characteristics of rebars in concrete exposed to different media and pipeline corrosion in sour-gas environment.

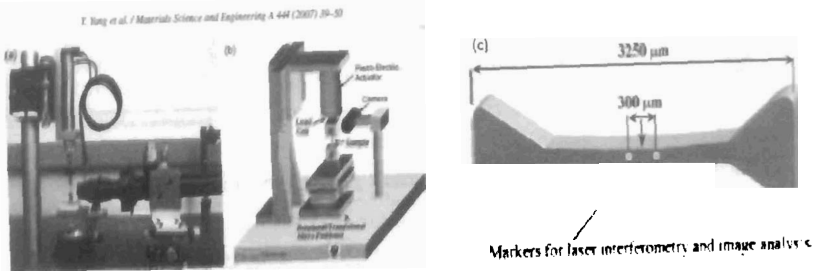
For my doctoral work, I drew up a proposal to develop a protocol for the production of ductile iron materials by adapting local technology and materials. I worked with Professors A. A. Afonja, J. A. Ali and O. O. Adewoye. I got the Deutscher Akademischer Austauschdienst (DAAD) fellowship to visit the Institut für Werkstofftechnik und Werkstoffprüfung, Techniche Universität Magdeburg, SKET Schwermaschinenbau and Stahl-Härterei GmbH, Hanover, Germany for my experimental work on the DI/ADI project. I completed the work in record time and I became the first candidate to graduate with a Ph.D in Materials Engineering in the Department.

I spent my second sabbatical leave at the Engineering Materials Development Institute (EMDI), Akure in 2006-2007, to work on some aspects of the DI/ADI research and build up a team of RDOs in DI/ADI technology. My visit was highly successful as the DI/ADI work recorded outstanding progress. To date, we have produced over a dozen Ph.Ds and over forty M.Sc. graduates with specialization in DI/ADI research and development. We have designed, fabricated and calibrated a number of equipment for DI/ADI research and development at the Institute. We've also produced a number of outstanding publications in this area of R&D. I was a consultant to some of NASENI Institutes/Centers on a number of cutting edge research projects.

I was a visiting research fellow to the Princeton Materials Institute (PMI) and Princeton Institute for the Science and Technology of Materials (PRISM), Princeton University, NJ, USA; in 2004-2005 and 2007 on US-Africa Materials Institute (USAMI) fellowships. I was also a visiting research fellow to the Thin Film Centre, University of the West of Scotland; UK. These are two highly esteemed centers of materials research and development, and I believe I made my mark by 'getting my hands wet', as they say, working on cutting-edge research in Micro- and Nano-electro-mechanical-systems (MEMS/NEMS) thin films and bulk nano-crystalline materials with Professors W. O. Soboyejo, A. A. Ogwu, Y. Yang, K. Lian, B. Boyce, etc. We indeed published a number of research articles in high-impact journals in materials science and engineering, in these areas of cutting-edge research and development. I am a pioneer member of the Nigerian Nano Technology Initiative (NNI). I was named to coordinate the recent Senate approved World Bank sponsored M.Sc. Nanotechnology program in OAU, with specialization in Nano-Medicine, Nano-Energy, Nano-Genomics and Nanostructured Materials.

My Contribution to Knowledge

Mr. Vice Chancellor sir, my research in the area of material properties' characterization and testing of LIGA Nickel Micro-Electro-Mechanical-Systems (MEMS) Thin Films and Nano-Crystalline (NC) Ni-Fe Bulk Alloys has provided useful data on their tensile, impact and fatigue properties as well as on their fracture/failure modes, with the objective of assessing their reliability, performance and to probe the mechanisms underlying their mechanical responses (Yang, et al (2007a, b, c and d, 2008).




ELSEVIER

Materials Science and Engineering A 444 (2007) 39–50

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

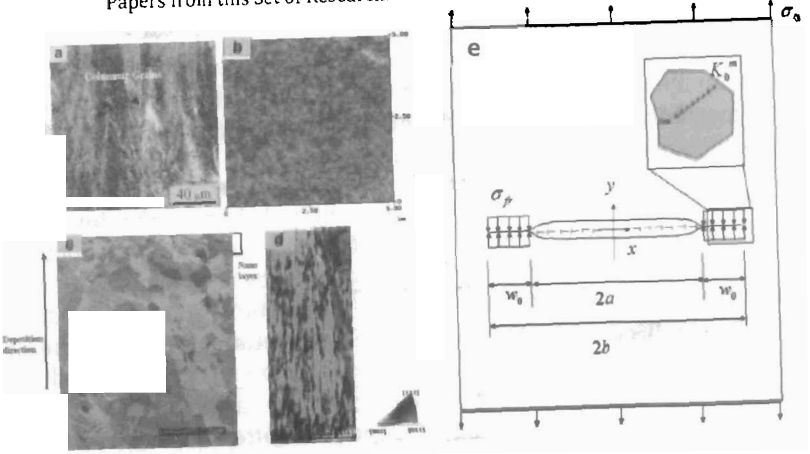
Mechanisms of fatigue in LIGA Ni MEMS thin films

Y. Yang[a], B.I. Imasogie[a,d], S.M. Allameh[a], B. Boyce[b], K. Lian[c], J. Lou[a], W.O. Soboyejo[a]

[a] Princeton Institute for the Science and Technology of Materials, Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544-5363, United States
[b] Mechanical Reliability and Modeling Department, Sandia National Laboratories, Albuquerque, NM 87185, United States
[c] Center for Advanced Microstructures and Devices, Baton Rouge, LA 70806, United States
[d] Department of Metallurgical and Materials Engineering, Obafemi Awolowo University, Ile-Ife 220005, Nigeria

Received 18 March 2005; received in revised form 22 June 2006; accepted 22 June 2006

Figure 27: (a) Micro-Fatigue Testing System; (b) the Schematic of the Micro-Fatigue Testing System; (c) the Schematic of the Dog-bone Shape Specimen Used for the Micro-Tensile and Fatigue Testing Experiments; (d) Scanned Picture of the Front Page of One of Our Papers from this Set of Research.



Available online at www.sciencedirect.com

ScienceDirect

Acta Materialia 55 (2007) 4305–4315

Acta MATERIALIA

www.elsevier.com/locate/actamat

ELSEVIER

Nanoscale and submicron fatigue crack growth in nickel microbeams

Y. Yang [a,b], N. Yao [b], B. Imasogie [c], W.O. Soboyejo [a,b,*]

[a] *Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544, USA*
[b] *Princeton Institute for Science and Technology of Materials, Princeton University, Princeton, NJ 08544, USA*
[c] *Department of Metallurgical and Materials Engineering, Obafemi Awolowo University, Ile-Ife 220005, Nigeria*

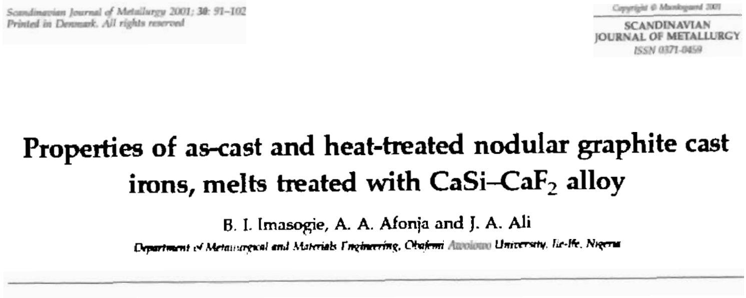
Received 5 September 2006; received in revised form 28 February 2007; accepted 23 March 2007
Available online 7 June 2007

Figure 28: Columnar microstructure of a LIGA Ni thin film: (a) optical microscopy image of LIGA Ni columnar microstructure; (b) AFM image of the top nanocrystalline grain layer; (c) FIB cross-sectional image of the graded grain structure; and (d) orientation microscopy (OIM) image of the LIGA Ni microtexture; (e) Model of the Coplanar Slip Band Emanating from the Tip of an Isolated Crack; (f) Scanned Picture of the Front Page of One of Our Papers from this Set of Research.

We have used a special state-of-the-art in-situ micro-fatigue testing system (Figure 26) that was developed at Princeton University for some of the works which have been published in the top five high impact international journals in materials science and engineering. One of the key contributions of this research is to demonstrate the ability of using an FIB-based technique to capture fatigue deformation, fatigue crack initiation and fatigue crack growth in complex grain MEMS structures at a very small scale. The dynamics and mechanisms of the prevailing fatigue processes were elucidated via FIB, OM, AFM, OIM, SEM, etc, techniques. In a summary, the results reveal that fatigue cracks grow by unzipping into intersecting slip bands that form during the cyclic deformation of notched microbeams.

My research has provided a basis for an integrated understanding of the micro-mechanisms of fatigue crack nucleation and growth in these advanced nano-materials and structures.

My research in the area of the development and characterization of ductile iron (DI), compacted graphite iron (CGI) and austempered ductile iron (ADI), has amply demonstrated the advantages in the use of specially formulated and designed calcium-magnesium based masteralloy nodularizers used in treatment for the production of this unique set of engineering purpose cast irons. My work has shown that lower nodularizer cost and cost-effective process windows are achievable without any deterioration in the mechanical properties, often associated with the conventional magnesium-ferrosilicon treated irons. In particular, the findings reported in my publications have contributed to the understanding of the factors which control the nucleation and growth of nodular graphite and desirable matrix microstructures, which have resulted in the improvement of the mechanical properties of these irons (Imasogie et al 2000, 2001, 2003a, 2003b, 2004, etc, Imasogie (2003, 2014, 2016)). I have in collaboration with Professor U. Wendt of the Institut für Werkstofftechnik und Werkstoffprüffung, TUM, Germany, developed and applied an efficient 3-D computer image processing and analysis technique for the quantitative evaluation of graphite nodularity in DI, which has been difficult and time consuming using manual stereological methods and conventional image analysis. The technological merit and scholarship in this research can be seen from considerations of metallurgical, mechanical and production (cost) benefits accruing from the development of these cast iron-based materials, as potential replacement for the rather expensive high grade alloy steels, and to the engineering materials development efforts in Nigeria.



Scandinavian Journal of Metallurgy 2001; 30: 91–102
Printed in Denmark. All rights reserved

Copyright © Munksgaard 2001
SCANDINAVIAN
JOURNAL OF METALLURGY
ISSN 0371-0459

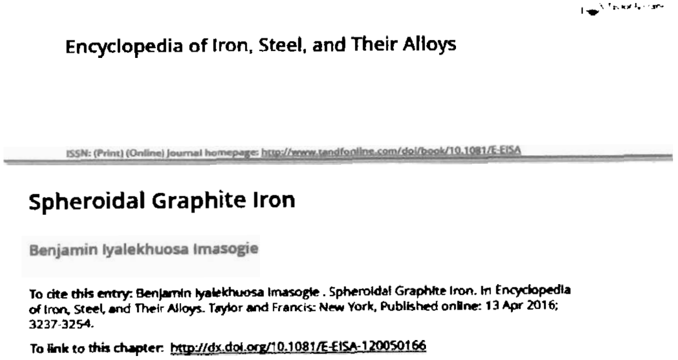
Properties of as-cast and heat-treated nodular graphite cast irons, melts treated with CaSi–CaF_2 alloy

B. I. Imasogie, A. A. Afonja and J. A. Ali

Department of Metallurgical and Materials Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria

Figure 29: Scanned Section of Front Page of One of Our Papers on DI-ADI Research.

My studies on the technical characteristics and reliability of some locally available clay minerals have provided data on their refractory, structural and insulating properties required for furnace construction to meet commercial standards. Data from this research have been used to design and fabricate a pre-heater/treatment ladle and a salt-bath furnace unit for the production of ductile (DI) and austempered ductile irons (ADI), at the Engineering Materials Development Institute (EMDI), Akure, Nigeria.



Encyclopedia of Iron, Steel, and Their Alloys

ISSN: (Print) (Online) Journal homepage: http://www.tandfonline.com/doi/book/10.1081/E-EISA

Spheroidal Graphite Iron

Benjamin Iyalekhuosa Imasogie

To cite this entry: Benjamin Iyalekhuosa Imasogie . Spheroidal Graphite Iron. In Encyclopedia of Iron, Steel, and Their Alloys. Taylor and Francis: New York, Published online: 13 Apr 2016; 3237-3254.

To link to this chapter: http://dx.doi.org/10.1081/E-EISA-120050166

Figure 30: Front Page of My Entry into the 65-Chapter of the Encyclopedia of Iron, Steel and Their Alloys. Taylor & Francis: New York, April, 2016

I have also contributed to knowledge in the area of evaluation of corrosion and corrosion fatigue effects on the properties of locally produced mild steels and concrete reinforcements (Rebars) in different media and highlighted the properties of special inhibitors for use in combating the corrosion menace prevalent in the building, construction and oil and gas sectors of the national economy. I have also carried out some studies to evaluate pipeline corrosion in sour-gas environments and in Friction-welded Superalloys. (Olorunniwo and Imasogie (2005); Olorunniwo et al (2007); Oluwasegun et al 2010, 2012).

10. Conclusions and Recommendations

Mr. Vice Chancellor sir, I have attempted in this lecture to expound some of the kernels of materials science and engineering, first as a renowned discipline and as a bedrock and major bridge interfacing and connecting all modern science and engineering fields and secondly, to establish the crucial role engineering materials play in human development and technological advancement. Every product we use in our daily lives is made of different types of materials; metals, plastics, ceramics, composites, semiconductors, biomaterials, etc. I have also attempted to show that while some disciplines may be considered to be "self-contained", independent of external conditions/influences, however, materials science and engineering is a dynamic and dependent field which is heavily influenced by technological development and the manufacturing industry, as much as it influences the latter. Thirdly, I have presented ample evidence to show that research and development in materials science and engineering have led to discoveries, novel new materials' structures, devices and products with outstanding properties, capacities, capabilities, etc., advanced manufacturing technologies, etc, all aimed at improving human lives, safety and all of which offers the field a promising future. I have argued that all students of the sciences and engineering disciplines should be properly equipped with fundamental knowledge in at least four primary inter-related topics of materials' structure, properties, processing and performance, to assist them to better appreciate their own disciplines. Fourthly, I have highlighted the various outstanding contributions to international materials research efforts by materials professionals in Obafemi Awolowo University, Ile-Ife and Nigeria in particular, and in the Diaspora in general.

I have also attempted to unravel the case of the abysmal situation of engineering materials development in Nigeria, despite our abundant 'wealth' in mineral, material and human resources, by highlighting Nigeria's 'catalogue of errors' in trying to develop the engineering materials and indeed the manufacturing sectors' base, as bedrock for technological development and advancement. I have shown that apart from the persistent poor planning and implementation strategies for important national projects, a penchant for mega or grandiose approach to development planning, over-politicization of national industrial projects, high level corruption, low commitment, poor funding, political instability, dismal state of technology infrastructure and non-conducive investment environment and support for SMEs; all contribute to worsen the situation of Nigeria's move towards technological development and/or industrialization.

I wish now to humbly make a few recommendations which might help in solving some of these problems of technological under-development of the country that have been highlighted above:

(i) There is a need to recognize that a strong materials education is necessary for technological development. All science and engineering students (both undergraduate and postgraduate) need to be presented with essential knowledge and skills to be able to choose the best materials for their design and manufacturing, as a fundamental step. Also, choosing proper materials for engineering designs requires fundamental knowledge of the direct relationship between application area, structure, properties and processing of materials. Sustainable development requires that the design engineer choose materials and processes that will have minimal environmental, health and safety impacts during the life of the product or system. It is hereby recommended that an introductory course in materials science and engineering should be prescribed for all science-based disciplines, while the present materials engineering minimum curricula prescribed by the NSE/COREN and NUC for engineering students should be revised to emphasize in addition, materials selection and innovation.

(ii) There should be visible progress on the decision by government to fast track training of post-graduate students by the first generation Universities in areas where they have comparative advantage. I am hoping that OAU will take up the challenges thrown up by her winning the hosting rights to the World Bank sponsored postgraduate program in Nanotechnology and leap-frog it to the level of a centre of excellence in Nano-energy, nano-medicine, nano-genomics and nano-structured materials, in the nearest future. We have what it will take to achieve this in OAU, if the program is properly funded and coordinated! There is an urgent need now to fast track University-Industry cooperation in research and development. This is one resource area and asset that the developed world utilized and continues to encourage in their technological advancement. We must do the same in Nigeria, if we want to achieve technological development.

It is now clear to all discerning minds that the pioneering effort of government in developing the engineering materials industry, particularly the petrochemical, aluminum, iron and steel, etc., has reached a critical mass. Private entrepreneurship should now be encouraged to take over, particularly the upstream and downstream sectors. The common adage that says: "Government has no business in business" should be made sacrosanct! For example, the defunct USSR (where private sector did not exist) collapsed essentially because it ran (rather very inefficiently), every major business from heavy industry to taxi scheduling. However, the successful transition/ transformation from the huge octopus that was NITEL to the competition-driven MTN-GLO-AIRTEL-ETISALAT, etc, era, is a prime example of how privatization can leap-frog technological development, even in Nigeria. Why can't this approach be tried for the power and steel industry?

The proposed privatization of the petroleum industry as prescribed by the petroleum industry bill, should be pursued to its logical conclusion, to take advantage of the benefits of competition. This must be well planned and ordered. However, there is an urgent need now to establish adequate private-industry-driven SMEs for local production of petroleum products for local consumption and export.

The government should as a matter of urgency, look into and drastically reduce the huge capital outlay for building and maintaining the now problematic (essentially because of vandalization, spillage, etc) oil and gas distribution-pipeline networks. The fund should have been used to modernize the national railway network to carry finished products from plants near the source of the primary (crude or raw materials) product. There is also a critical need to add value to the crude, raw and scrap materials being exported, at least to a semi-finished product level. This will also create needed jobs and conserve foreign exchange earnings.

The government should look into the improvement and achievement of stable power supply and transportation infrastructure. The appalling state of these sectors is a drawback on everything that has to do with development in Nigeria.

(vii) The steel sector roadmap is in dire need of rationalization. This must be pursued dispassionately, comprehensively and systematically to unravel the whole gamut, as they say; identify the problems, correct structural deficiencies and determine the direction of development. The current move to privatize most of these "parastatals" should be diligently and rigorously pursued. This must be done with determination, given the amount of money already sunk into the projects and the irreversibility of the investment.

(viii) A lot of developing countries are moving away from grandiose steel plants and processes. They are getting to realize and channel their efforts into cost-effective ferrous based products in the hue of ductile (DI) and austempered ductile iron (ADI) with comparable and even superior properties and processing advantages than high grade alloy steels in many applications. Why should Nigeria be stuck with steel plants that are now obsolete in countries where they were designed? As they say, there is "No use running when you are on the wrong road"! The DI/ADI research group in OAU and EMDI, Akure has the expertise and capability to produce and advice on production protocols and processing windows on this unique class of engineering purpose cast irons; if called upon.

(ix) Nigeria should strive to envision a more realistic, achievable vision or development plan. If Nigeria rates 141st to 181st out of 186 countries of the world on all vital development indices in 2009, it is difficult to see how the country can emerge in the top twenty by 2020! Thus, the so-called Vision 20 20 is clearly unrealistic and it is even a ridiculous over-ambition on our part. Apart from playing to the gallery, it shows that the country has no clue about development planning strategies, including setting achievable goals.

REDEDICATION AND ACKNOWLEDGEMENTS

Mr. Vice Chancellor sir, for me, this day represents the end of the beginning of an active academic career in teaching and research in materials science and engineering, and a unique occasion to rededicate myself to a profession which I chose over three decades ago and for which I am hoping to make further modest contributions to, in the coming years.

I post-humously appreciate the simplicity of the lives of my parents, Pa. Thomas O. and Madam Esohe I. Imasogie, who although they never had any formal education themselves, knew the value of education and ensured that their children and others under their care got the best out of school and available vocational training. I salute my dear Uncle; Revd. Prof. Osad. Imasogie, Ph.D., CON; the only one left of my father's kindred, for lovingly filling the void he left behind.

There are special people to be mentioned here for special thanks; my mentors (Profs. A. A. Afonja, O. O. Adewoye (Late), E. O. B. Ajayi, M. O. Faborode, W. O. Soboyejo, U. Wendt, H. Blumenauer, etc.), former lecturers, former students, co-researchers, professional colleagues, Pastors (Revds. G. Maradesa, Prophet M. Oyatumo, Dr. T. Olu Aibinuomo, etc.) and many friends, for positively impacting my life and career. I would also like to express particular appreciation to the founding fathers and individual members of this great citadel of learning; Obafemi Awolowo University, Ile-Ife. I first came here about 38 years ago and it has remained for me, the reference point for educational progress in sub-saharan Africa! Great Ife!

I acknowledge the Deutscher Akademischer Austauschdienst (DAAD) for awarding me a Fellowship to visit the Institut für Werkstofftechnik und Werkstoffprüfung, Techniche Universität Magdeburg, SKET Schwermaschinenbau and Stahl-Härterei GmbH, Hanover, Germany (1992-93) for my experimental work as a visiting doctoral student. I am indebted to the US-Africa Materials Institute (USAMI) for visiting Fellowships to visit the PMI-PRISM, Princeton University, NJ, US (2004-05, 2007) and the University of West Scotland for a Fellowship to visit the University's Thin Film Center in 2006. These visits have indeed exposed me to modern techniques in materials research in general and nanostructured materials in particular.

I am most grateful to God for my co-presenters of this lecture: Prof. (Mrs.) Mosunmola O. Imasogie and Mr. Abimbola Benjamin Imasogie. God has used you above all to provide succor and unflinching support for me and to make this day a joyous one. May God do the same in your lives too and in the lives of all those who are present here today. Amen! Our dear angel; Adesuwa Lauretta Omolola Imasogie (1986-2007) post-humously share in today's glory and joy.

Mr. Vice Chancellor sir, while thanking my audience for their attention, I wish all to join me in praise to the Almighty, All-knowing, and the Creator of all living and non-living (materials) things; by chorusing thus:

All things bright and beau - ti - ful, All things great and small,
All things wise and won - der - ful; Our Fa - ther made them all.
Each lit - tle flower that o - pens, Each lit - tle bird that sings;
He made their glow-ing col - ors, He made their ti - ny wings.

Cold wind in the win - ter, Pleas - ant sum - mer sun,
Ripe fruits in the gar - den; He made them ev - 'ry one,
He gave us eyes to see them, And lips that we might tell
How good is God our Fa - ther Who do - eth all things well.

Amen!

THANK YOU ALL!!!

REFERENCES

Adams, J and Pendlebury, D. (2011). Global Research Report. *Materials Science and Technology*, June 2010. www.grr.materialscience.pdf.

Additive Metal Parts.htm (2015). *Engineering Materials*. December 2015.

Afonja, A. A. (1986). Materials, Energy and the Environment. *Inaugural Lecture Series 80*. February 11, 1986. Obafemi Awolowo University Press. Ile-Ife, Nigeria, 1986.

Afonja, A. A. (1989). Planning Strategy and Appropriate Technology for Small Scale Industrialization: A Case Study of the Traditional Metal Founding and Metalworking Industries in Nigeria. International Research Development Centre (IDRC), Canada.

Afonja, A. A. (2002). The World of Materials – A Keynote Address. *Proceedings of the Nigerian Materials Congress/N-MRS (NIMACON – 2002)*. EMDI, Akure, Nigeria. Nov. 11-13, 2002.

Afonja, A. A. (2009). Technology for Development: A Roadmap for Nigeria, *Faculty of Technology Lecture*, Obafemi Awolowo University, Ile-Ife, Nov. 2009.

Ahmed, M. E. and Song, J. B. (2012). Non-Parametric Bayesian Human Motion Recognition Using a Single MEMS Tri-Axial Accelerometer. *Sensors*, 2012, 12, 13185-13211; doi: 10.3390/S121013185.

Allendorf, M. D. and Hesketh, P. (2016). Metal Organic Frameworks for Chemical Recognition Sensing and Measurement. Spie.org/ newsroom/1512-metal-organic-frameworks-for-chemical-recognition.html.

Anon. (2010). Classification and Selection of Materials. www.000901.pdf

Anon. (2014). Introduction: Classification and Properties of Materials. www. 002212. pdf

Anon. (2015). Introduction to Microelectromechanical Systems (MEMS) _ Complaint Mechanism.htm.

Anonymous Editorial (2010). "A Bright Future for Materials Research". *NPG Asia Materials*. January 21, 2010. http://www.natureasia.com/asia-materials/editorial.php?id=687.

Armoco online Ballistic Kevlar Fabrics.htm. ArmorCo Advanced Armoring Products. A Division of Infinity Composites Inc. www. infinityfrp.com.

Ashby, M. F. and Cebon, D. (2007). Teaching Engineering Materials.pdf. The CES Edu Pack, Engineering Department. Cambridge University, England. May 2007.

Ashley, S and Greenemeier (2013). Nano Products online Store. mknano.com/? gclid=cjz275Gky8sCFZadGwod728FfQ. htm. *Scientific American*. April 22, 2013.

Atanda, P. O; Olorunniwo, O. E; and Imasogie, B. I. (2013). "Effect of Ca–Mg and MgFeSi Graphite Nodularizers on the Nodular Graphite

Characteristics of Ductile Cast Irons," *Materials Performance and Characterization*, Vol. 2 (1), 2165-3992, 391–399.

Austen-Morgan, T (2015). Tyres that Repair Themselves, *Engineering Materials* 25 Sept 2015.

Boardman, C. (2015). www.chrisboardman.com

Brandenberg, K., Ravenscroft, J., Rimmer, A. and Hayrynen, K. (2001) An ADI Crankshaft Designed for High Performance in TVR's Tuscan Speed Six Sports Car. *Automotive Castings Processes and Materials*, SAE World Congress, March 2001.

Briggs, G. A. D. (1995). Materials Science education from School to University. *Materials Science and Engineering A*. 199(1), 89-794. Doi: 10:1016/0921-5093(95) 09915-8.

Britannica Encyclopedia Online (2016).www.britannica.com.au/britannica-online /2016/.

Chang, J. M. (2013) Iron Man-like Body Armor for Soldiers in the Works. *abc News*, Oct. 10, 2013.

Cunningham, J. (2013). Quantum Tunneling Composite (QTC)., *Engineering Materials*, Dec. 2013.

Cycling Weekly (2016). http:www.cycling weekly.co.uk/news/latest/-news/chris-boardmans/march2016.htm

DailyPost (2016). Why FG will not Touch Ajaokuta - Fayemi. Dailypost Staff, *@dailypostngr*. May 26, 2016

Das, A., Sallat, A., Böhme, F. Suckow, M., Basu, D. Wieβner, S. Werner-Stöckelhuber, K. Voit, B. and Heinrich, G. (2015). Ionic Modification Turns Commercial Rubber into a Self-Healing Material. *ACS Appl. Mater. Interfaces*, 2015, 7 (37) pp 20623-20630. Doi: 10.1021/acsami.5b05041.

Denso Coropration (2014). http://www.denso-Int.com, *Science News* (2014).

Dixon, R. and Bouchard (2007). Prospect for MEMS in the Automotive Industry. *MEMS Journal*, August 09, 2007.

Ernst, P (2010). MEMS @ BOSCH: Automotive Applications and Beyond, http://www.findmems.com/mems-bosch-automotive-applications-and-beyond/About mems.htm. Dec. 13, 2010.

Eureka (2014). Sensor-Sensing Presence or Absence of Objects. New Ideas in Technology.htm.

Fagg, B. (1969) *World Arch*. 1, 41.

Flemings, M. and Cahn, R. (2000). Organization and Trends in Materials Science and Engineering Education in the US and Europe. *Acta Materialia*, 48 (1), 371-383, doi: 10.1016/51359-6454 (99)00305-5.

Fonseca, M. and Newton, P. (2015). 10 Amazing Innovations for 2015. www.intelligenthq.com/innovation-management/10-amazing-innovations-for-2015/.

Galway Education Centre (2008). T4: Technology Subjects Support Service. *Materials Technology*. Classification of Materials.ppt.

Galway Education Centre (2013). Reduction Gear System.htm.

Granta Design Limited. (2014). Granta's CES Edu Pack. http://www.grantadesign.com/education/index.htm.

Guesser, W. L; Koda, F; Martinez, J. A. B. And da Silva, C. H. (2012). Austempered Ductile Iron for Gears, *SAE International*, adi-engrenagens.pdf. 2012-36-0305.

Hayrynen, K. L., Brandenberg, K. R. and Keough, J. R. (2002). Applications of Austempered Cast Irons. *AFS Transactions* 02-084, 1-10.

Hitachi Metals Ltd (2002). Gears Made of Austempered Ductile Irons, Copyright 2002. http://www.hitachi-metals.co.jp/e/prod/prod06/p06_03_C.html

Hopperton, L. (2013). TPU 92 A -1- the First Fully-Functional Flexible Materials for 3D Printing. *Engineering Materials*, 22 April, 2013.

Hupfield, F. (1899): Mitt. a. d. deutschen Schutzgebieten, 12, 175.

IAEA (2012). IAEA Training Course Series No. 52. IAEA/TCS/52. IAEA, Vienna, March, 2012. http://www.iaea.org/books. TCS-52_web.pdf

Ilyas, M. and Mahgoub, I. (2005). Smart Dust: Sensor Network Applications, Architecture and Design. CRC Taylor and Francis, 2005.

Imasogie, B. I. (1994). Development and Characterization of Isothermally Heat-Treated Nodular Cast Irons. Ph.D. Thesis. Obafemi Awolowo University, Nigeria. (Unpublished).

Imasogie, B. I; Afonja, A. A and Ali, J. A. (2000) Properties of Ductile Cast Iron Nodularised with a Multiple Calcium-Magnesium Based Master Alloy. *Materials Science and Technology*. Vol. 16, No. 2, 194-201.

Imasogie, B. I; Afonja, A. A and Ali, J. A. (2001) Properties of As-cast and Heat-treated Nodular Graphite Cast Irons, Melts Treated with CaSi-CaF_2 Alloy. *Scandinavian Journal of Metallurgy*, 30, 2, 91-102.

Imasogie, B. I. (2003). Optimum Ca-CaC_2-Mg Masteralloy Concentration Requirements in Graphite Nodularising Rtreatments of Cast Iron. *Materials Engineering*. Vol. 14, No. 1, 77-86.

Imasogie, B. I; and Afonja, A. A. (2003). Effect of Austempering on the Microstructure and Impact Toughness of Ductile Iron; *Materials Engineering*, Vol. 14, No. 3, 251-259.

Imasogie, B. I (2003) Microstructural Features and Mechanical Properties of Compacted Graphite Iron Treated with Calcium-Magnesium Based Masteralloy. *Journal of Materials Engineering and Performance*, Vol. 12, No. 3, 239-243.

Imasogie, B. I. and Wendt U. (2004) Characterisation of Graphite Particle Shape in Spheroidal Graphite Iron Using a Computer-based Image Analyzer. *Journal of Minerals & Materials Characterization & Engineering, (jmmce.org)*. Vol. 3, No.1, 1-12.

Imasogie, B. I. (2016). Spheroidal Graphite Iron: Characterization. In: Encyclopedia of Iron, Steel, and Their Alloys. Taylor & Francis: New York. Published Online: 13 April, 2016, 3237-3254. http://dx.doi.org/10.108/E-EISA-120050166.ISBN:1-4665-1104-4. eISBN:1-4665-1105-2.

Kahn, J. M; Katz, R. H. and Pister, K. S. J. (2000). Emerging Challenges, Mobile Networking for "Smart Dust", *Journal of Communication and Networks*, 2 (3), 188-196, 2000.

Kamila, S. (2013). Introduction, Classification and Application of Smart Materials: An Overview. thescipub.com/pdf/ajassp/2013.876.880.pdf. *American Journal of Applied Sciences*, 10 (8); 876-880.

Keough, J., Austempered Materials and their Applications to Drive Line and Suspension Components. SAE International Off-Highway and Power plant Congress , March 2001.

Keskin, S. and Kizilel, S. (2011). Biomedical Applications of Metal Organic Frameworks. Industrial & Engineering Chemistry Research (I&EC). Research.pubs.acs.org/IECR.www.ku.edu.tr/~skizilel/ie101312_2011.pdf.

Kolesar, Jr., E. E., Reston, R. R., Ford, D. G. and Fitch, Jr. R. C. (2007). Multiplexed Piezoelectric Polymer Tactile Sensor. *Journal of Robotic/Systems*. Volume (,Issue 1, 13 Mar. 2007. (DOI: 10.1002/rob.4620090104).

Larson, L. (2014). The 10 Best Technology Advances of 2014. Tech Lists Paste.htm. Dec. 2014.

Leibinger, P. (2015). Laser Metal Fusion (LMF) and Laser Metal Deposition (LMD), Additive Metal Parts.htm. *Engineering Materials*, December 2015.

Leuschner, C., Kumar, C., Urbina, M. O., Zhou, J., Soboyejo, W. O., Hansel, W. and Hormes, F. (2005). The Use of Liquid Conjugated Superparamagnetic Iron Oxide Nanoparticles (SPION) for Early Detection of Metastases. *NSTI - Nanotech* 2005. www.nsti.org. Vol. 1, 2005.

Lotus Engineering Report (1992). Lotus Engineering, UK. LOYUS News – Road & Track.

Mädler, K., (1999). On the Suitability of ADI as an Alternative Material for (Railcar) Wheels. English Translation, *GIFA*, June 1999, Dusseldorf, Germany.

Madou, M. (2002). Fundamentals of Microfabrication: the Science of Miniaturization; CRC Press, New York, NY. 2002.

Magee, C. L. (2012). Towards Quantification of the Role of Materials Innovation in Overall Technological Development. 26-chfquantificationofmaterialsrole.pdf.

McWhorter, P. (2008). MEMS. About MEMS.htm

Meng, J., Fan, J., Galiana, G., Branca, R. T., Clasen, P. L., Ma, S., Zhou, J., Leuschner, C., Kumar, C. S., Hormes, J., Otiti, T., Beye, A. C., Harmer, M. P., Kiely, C. J., Warren, W., Haataja, M. P., and Soboyejo, W. O. (2009). LHRH-Functionalized Superparamagnetic Iron Oxide Nanoparticles for Breast Cancer Targeting and Contrast Enhancement in MRI. *Materials Science and Engineering C.* 29,1467–1479.

MEMSBLOG (2016). What is MEMS? Blog. MEMS/What is MEMS-MEMS & Sensors Industry Group.htm. Feb 25, 2016.

Metallurgist (2013). Classification of Materials, Their Properties and Uses.htm.

MIT Technology Review (2015). Advanced Manufacturing and New Materials. http://www.technologyreview.com/news/_ 424631/ advanced-manufacturing....htm.

MOF Technologies Ltd (2012). Metal-Organic Frameworks. www.moftechnologies.com/MOFs.html.

Mukasyan, A. (2014). Lecture_1_2014._ Lecture.pdf; www.nd.edu/~ amoikais/CBE 30361, http://Sakai.nd.edu

Nash, G. (2015). New Research Exploits Extraordinary Properties of Graphene. *Nature Communications.* Science Daily.com/ releases/2015/11/151130130035.htm

National Academy of Engineering (2004). The Engineer of 2020 Visions of Engineering in the New Century. Washington, D. C. The National Academies Press.

National Academy of Engineering (2005). Educating the Engineer of 2020: Adapting Engineering Education in the New Century. Washington, D. C. The National Academies Press.

National Research Council (1989). Materials Science and Engineering for the 1990s. Maintaining Competitiveness in the Age of Materials (1989). www.nap.edu/read/w435/chapter/2#16.

Olorunniwo, O. E. and **Imasogie, B. I.** (2005) Internal Corrosion Monitoring and Control in Sour Gas Systems. *Materials performance*, Vol. 44, No. 8, 36-39.

Olorunniwo, O. E., **Imasogie, B. I.** and Afonja, A. A. (2007) Evaluation of Pipeline Corrosion in Sour-Gas Environment. *Anti-Corrosion Methods and Materials.* Vol. 54, No. 6, 346- 353

Oluwasegun, K. M; Olorunniwo, O. E. and **Imasogie, B. I.** (2010). The Role of Constitutional Liquation of Primary Strengthening Phases in Improving the High Temperature Performance of Inertia Friction Welded PM RR1000 Superalloy. *NJMSE*, Vol.2 (1), 13-19.

Oluwasegun, K.M; **Imasogie, B. I.**, Olawale, J. O., Oyatogun, G. M. and Shittu, M. D. (2012). TEM Characterization of the Order-Disorder Transformation of RR1000 γ' Precipitates. *NJMSE*, Vol. 3 (1), 1-7.

Oluwole, O.O., Atanda, P. O. and **Imasogie**, B. I. (2009). Finite Element Modeling of Heat transfer in Salt Bath Furnaces, *Journ. Minerals and Materials Characterization and Engineering*, Vol. 8. No. 3, 229-236.

Oni, Y., Hao, K. Dozie-Nwachuku, S. Obayemi, J. D., Odusanya, O. S., Anuku, N. and Soboyejo, W. O. (2014). Gold Nanoparticles for Cancer Detection and Treatment: The Role of Adhesion. *Journal of Applied Physics*, 115, 084305 (2014): doi: : 10.1063/1.4863541.

Osasona, O. (2015). Electronic Devices in the Service of Man. *Inaugural Lecture Series 280*, 24th November, 2015. Obafemi Awolowo University Press, Ile-Ife, Nigeria. 2015.

Palsenbarg, V. (2014). www.materialise.com/blog/material-monday-fantastically-flexible-tpu-92a-1/

Poch, J. (2007). I1_Classification.pdf

Ryan, V (2001). WHAT IS KEVLAR. TYPES OF KEVLAR.htm.

Science News (2014). New Study Reveals Communications' Potential of Graphene, *Science Daily*, Feb. 19, 2014.

Science News (2015). Super-Absorbent Material Soaks up Oil Spills. *Science Daily*, Nov. 30, 2015.

Science News (2016). Novel Graphene, *Science Daily*, Feb. 18, 2016.

Scientific American (2016). Nano Products Online Store. mknano.com/?gclid=cJz275Gky8sCFZadGwod728FfQ.htm.

Stark, L. D. (2016). EPSON Shows off Augmented Reality with OLED Glasses. *Gadget Guy Australia* 18/03/2016.

Tanaka, Y and Kage, H. (1992), Development and Application of Austempered Spheroidal Graphite Cast Iron. *Matls. Trans. JIM*, 33, 6, 543-557.

Templeton, E., Martin, A-M. and Moore, A. (2014). Materials Breakthroughs You Should Know.htm

The National Academies Press (1974). Materials and Man's Needs: Materials Science and Engineering Summary Report of the Committee on the Survey of Materials Science and Engineering. Chapter: Science and Engineering in Materials Activities. National Academy of Sciences Press. Washington D.C. 31974, www.nap.edu/ read/10435/ chapter/2. pg. 1-218.

Tsipas, S. A. and Olmos, D. Topic 1.1. Introduction, Families of Materials and Applications. www.uc3m.es. T1.1_autor.pptx - Chapter_1_1.pdf. (Retrieved May 12, 2016).

Tylecote, R. F. (1970). *Bull. HMG.* 1970, 4 (2), 67.

UNDP (2001). Human Development Report.

US Department of Energy Fuel Cell Technology Program (2010). Fcth2_Fuel cell_factsheet. pdf (2000).

White House Press (2016). President Obama Honors Extraordinary Early Career Scientists and Engineers (PECASE). https:// www.whitehouse.gov/ the-press-office/2016/05/09.

Wood, J. (2008). The Top Ten Advances in Materials Science. *Materials Today*, Jan-Feb. 2008, Vol. 11 No. 1-2. 40 pp.

Woodford, C. (2016). How does Bulletproof Glass Work-Explain that stuff.htm

www. 002212. pdf (Retrieved December 2015)

Yang, Y. Allameh, S., Lou, J., **Imasogie, B. I.**, Boyce, B. L. and Soboyejo, W. O. (2007), Fatigue of LIGA Ni Micro-Electro-Mechanical-System Thin Films, *Metall & Matls. Trans. A*, Vol. 38, No. 13, 2340-2348.

Yang, Y.; **Imasogie, B. I;** Allameh, S. M.; Boyce, B.; Lian, K.; Lou, J. and Soboyejo, W. O. (2007) Mechanisms of Fatigue of LIGA Ni MEMS Thin Films. *Materials Science and Engineering A*; Vol. 444, 1-2, 39-50.

Yang, Y.; **Imasogie, B. I;**. Fan, G. J. Liaw, P. K. and Soboyejo, W. O (2008) Fatigue and Fracture of a Bulk Nanocrystalline Ni-Fe alloy, *Metallurgical and Materials Transactions A*. Vol. 39A, No. 5, 1145-1156.

Yang, Y.; Yao, N. **Imasogie, B. I.** and Soboyejo, W. O. (2007) Nanoscale and submicron fatigue crack growth in Nickel microbeams. *Acta Materialia*, Vol. 55, 4305–4315.

Yescas-Gonzalez, M. A. (2001). Modelling the Properties of Austempered Ductile Cast Iron. Ph.D. Thesis University of Cambridge, http://www.msm.cam.ac.uk/phase-trans/2004/adi3.html