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Understanding Ceramic Science and Technology beyond Clay

Adindu C. Iyasara*, Isiaka O. Odewale, Emmanuel O. Nwabineli, Nobert O. Osonwa, Thaddeus C. Azubuike and Victor T. D. Amaakaven
Department of Ceramic and Glass Technology, Akanu Ibiam Federal Polytechnic Unwana, Nigeria
*Corresponding author: Email: acnnayerugo@gmail.com | Phone: +2348037390071

Abstract: *Most unprofessional opinions limit the study of ceramics to clay. No doubt, early ceramics originated from clay minerals, hence development of traditional ceramics such as refractories or refractory ceramics and other items like tiles, sewage pipes, porcelain, table and sanitary wares. Traditional ceramics opened the window for ceramic arts, science, engineering and technology. As technology evolves, ceramics develop from traditional ceramics to advanced ceramics. In this opinion paper, the erroneous impression of constraining ceramics to clay is corrected. The impact of electroceramics (a major branch of advanced ceramics) in modern technology is highlighted. Due to the influence of electroceramic materials in telecommunications, electronics, transportation, medicine, space exploration and other related fields, they are regarded as the hub of modern technology.*

Key words: *Ceramics, Clays, Electroceramics, Advanced ceramics, Electronics.*

1. Introduction

Ceramics is one of the oldest professions and dates back to ancient times. Early ceramics originate from clay minerals. In order words, clay is the major natural raw material for the production of early known ceramics. Those ceramics made from clay as the main precursor are known as traditional ceramics, e.g., earthenware, cement, refractories, tiles, sewage pipes, tableware, sanitaryware, etc. Traditional ceramics are classified as structural ceramics and have evolved over many centuries and will continue to be indispensable. The term “Ceramic” is derived from the Greek word “Keramikos”, meaning potters’ clay (Iyasara et al., 2014; Knapp, 2003). Due to this original background, ceramic is generally seen as anything made of clay. Today, ceramics have a wide concept, and defined as solid compounds that are formed by the application of heat and/or pressure and comprise of at least one metal and non-metallic elemental solid (NMES) or a non-metal or a combination of at least two NMES and a non-metal (Iyasara et al., 2014; Idenyi, 2002). With this broad definition of ceramics, all oxides, nitrides, borides, carbides and silicides are ceramics.

Clay is a complex alumino-silicate compound that contains attached water molecules (Iyasara et al., 2016; Idenyi, 2002). It is a plastic material containing fine grained minerals which during drying or sintering hardens thereby losing the attached water molecules (Ameh & Obasi, 2009; Hassan & Aigbodion, 2014). Clay mineral is the most common and abundant mineral on earth (Iyasara et al., 2014) and the industrial products derivable from clays include refractories, bricks, tiles, cement, drilling mud, catalysts, etc. (Ibude & Agholor, 2012).

Ceramics are generally classified into two major types; traditional ceramics and advanced ceramics. The traditional ceramics as already discussed are called traditional because they have been in existence and in use for ages, and possess similar molecular structure with earthenware. Advanced ceramics, also known as modern ceramics are made using inorganic, synthetic powders or compounds with high percentage purity through series of specialised manufacturing processes (Richerson & Lee, 2018). Advanced ceramics are becoming increasingly important in engineering and technology, and are playing crucial roles in electronics, energy, telecommunication, transportation, medicine, defense and space exploration. Examples of advanced ceramics include alumina, zirconia, silicon carbide/ nitride, zinc oxide, titania-based ceramics, e.g., strontium titanate ($SrTiO_3$), barium titanate ($BaTiO_3$), titanium oxide (TiO_2), etc.

2. Concept and Applications of Electroceramics

An electroceramic is a major branch of advanced ceramics that are employed in a wide range of electric, optical, magnetic and medical applications. Unlike traditional ceramics, eletroceramics are a relatively new phenomenon and were developed during the second world war. Since then, electroceramics have created a profound impact on the technological development and total wellbeing of developed nations. Applications and utilizations of electroceramics including the following:

i. Electronics

Eletroceramics with low dielectric constant or relative permittivity (i.e., low electric resistivity and high dielectric strength) are fabricated into substrates for integrated circuits (also known as silicon chips) (Knapp, 2003). No computer, modern car, washing machine, etc. can function without an integrated circuit. The base for a chip contains a thin film of 99.5 % alumina with the remaining being SiO_2 and MgO ceramics and created by draping a paste (mixture of Al_2O_3, SiO_2 and MgO) onto a tape and heated. A modern integrated circuits contain millions of transistors and diodes, comprising about 20 layers that can be achieved via up to 80 clean room fabrication steps (Richerson & Lee, 2018).

ii. Ceramic Capacitors

Electroceramics with high dielectric constant (i.e., low dielectric strength) are used in capacitors. Capacitors are tiny devices designed to store electricity in an electronic circuit (Knapp, 2003). It consists of two metal plates separated by an insulator. Outside energy storage, capacitors in an electric circuit can function as blocking, coupling, decoupling, by passing, filtering and transient voltage suppression or arc suppression (Richerson & Lee, 2018). Presently, ceramics and polymers are the most used dielectric materials for capacitors.

Multilayer ceramic capacitors (MLCCs) are produced by stacking layers of conducting electrodes with each separated by a thin layer of ceramic dielectric material

(Idu et al., 2016; Moulson & Herbert, 2003). MLCCs are usually made of barium titanate ceramic ($BaTiO_3$) its inherent high dielectric constant. The high dielectric constant of $BaTiO_3$ ceramics is due to the perovskite crystal structure (Idu et al., 2016; Richerson & Lee, 2018). Ceramic capacitors are primarily used in small-capacitance applications such as mobile phones, consumer electronics, personal computers, peripherals and microprocessors. They form the heart of computer memory chips such as random access memory (RAM) and dynamic random access memory (DRAM) (Knapp, 2003).

iii. Piezoelectric Ceramics

Some electroceramic materials exhibit piezoelectricity (also known as pressure electricity). It is the development of strain in a material upon application of an electric field. Thus, piezoelectrics are materials that produce an electric voltage when they are pushed, pulled or twisted. Piezoelectric phenomenon has led to the vast use of piezoelectric ceramics as transducers in microphones, strain gauges, accelerometers, ultrasonic devices, sonar devices (underwater object detectors), home doorbells, gas stove igniters, etc. (Knapp, 2003; Richerson, 2006). Quartz (Silica) is the most important ceramics that exhibit piezoelectricity. Other examples of piezoelectric ceramics are $BaTiO_3$, $PbTiO_3$, etc.

iv. Magnetic Ceramics

There are some metal oxide ceramics that are naturally magnetic, hence they behave like iron magnets. These ceramics that exhibit magnetic behaviour are called ceramic magnets (ceramets). The first magnets were naturally occurring ferrous ferrite, Fe_3O_4 (ceramic magnetite) (Richerson, 2006). Magnetic ceramics are made of ferrites which are crystalline minerals composed of iron oxide and other metals. The general chemical formula is $M(Fe_xO_y)$ where M represents other metallic elements than iron. Ferrites acquire magnetic moment in the presence of magnetic fields, e.g., Fe, Ni, Co and related compounds. Magnetic ceramics have widespread industrial applications such as cores in aerials (ferrite rods) for portable radios, loudspeakers, television receivers, magnetron oscillators, transformers, etc. (Gupta & Kumar, 2004; Knapp, 2003; Richerson, 2006).

Generally, magnetic ceramics are used to provide permanent storage of information in computers. For example, all magnetic tapes for video, audio and/or computer data are plastic in nature but coated with ferrites. In "Stealth Technology" (a recently developed technology), military aircrafts are made visible by coating them with ferrites-rich paints.

v. Electro-optic Ceramics

With the application of electric filed, some electroceramics exhibit changes in optical properties. This phenomenon is known as "Pockels effect". The class of ceramics that showcase a change in refractive index relative to electric filed is known as electro-optic ceramics (Hench & West, 1990; Moulson & Herbert, 2003). Broadly, electro-optic ceramics are materials that exhibit the "Pockels effect" where the refractive index change is proportional to the electric strength.

Typical examples of electro-optic ceramics include $LiNbO_3$, $LiTaO_3$, $Ca_2Nb_2O_7$, $BaNaNb_5O_{15}$, etc. electro-optic ceramics are useful in the following areas:

a. Controllable optical devices e.g., lenses, prisms, switches, couplers, etc.
b. Design of creative memory devices, e.g., rewritable memory disk.
c. Electro-optic ceramics are used to convert an optical beam at one frequency to an optical beam at a different frequency

d. In the production of flash goggles, electro-optic ceramics are used. For example, pilots of military aircraft and arc welders wear flash goggles to prevent their eyes from the effects of nuclear flash and radiations, respectively.

Some electroceramic crystals are transparent. Due to this property, they are utilized in making high quality camera lenses, e.g., fluorite for sharpness of image. Most bright lights used in stadia and as street lights do not have glass casing or enclosure but transparent ceramics of Al_2O_3 and MgO (Knapp, 2003). An enclosure of transparent ceramics is preferable because it has the capacity to withstand extreme high temperature while glasses in such a condition will crack.

vi. Ceramic Phosphors and LASERS

Phosphorescence is an important optical property exhibited by some electroceramics. It is the emission of light resulting from the excitation of the material by heat, electricity, x-rays, light or any appropriate source of energy (Knapp, 2003; Richerson, 2006; Richerson & Lee, 2018). Ceramics that exhibit this characteristic are known as ceramic phosphors. These ceramics are used in fluorescent lights, oscilloscope screens, television screens, photocopy lamps and other related applications (Burrus, 1972). Ceramic phosphors are usually doped for effective performance, e.g. sb- and Mn-doped $Ca_5(PO_4)_3(Cl,F)$, $Sr_5(PO_4)_3(Cl,F)$ for fluorescent lights; Mn-doped $Zn_3(PO_4)_2$, Eu-doped YVO_4 and Y_2O_2S for TV screens and Mn-doped $MgGa_2O_4$ ceramics for photocopy lamps.

LASER is an acronym and it stands for "Light Amplification by the Stimulated Emission of Radiation" (Richerson, 2006). The first LASER was invented in 1960 (Knapp, 2003) and it uses Cr-doped Al_2O_3 ceramics (ruby laser) to amplify light from a flash bulb. Other important ceramics for laser applications include Nd-doped $Y_3Al_3O_{12}$ (Yttrium aluminium garnet, YAG) and Nd-doped glass. Semiconductor lasers also use ceramics for junctions and substrates.

vii. Ceramic Pigments /Colourants

Ceramic colourants are widely used as pigments in paints and glazes at both low and high temperatures. The ceramic pigments in paints are mainly rare-earth and transition-based ceramics, e.g., cobalt aluminate, cobalt silicate, tin-vanadium oxide, etc. Because ceramic colourants are inert, they are required where processing is performed at elevated temperatures. For example, a glazed porcelain that is fired at 750-850 ^oC requires a ceramic colourant , e.g. spinel structure (AB_2O_4) ceramics such as blue $CoAl_2O_4$ ceramics (Richerson, 2006). For a very high temperature application (1000-1250 ^oC), doped ZrO_2 and $ZrSiO_4$ ceramic pigments are used. These colourants possess increased resistance to attack by glass.

viii. Conductive Ceramics and Sensors

Electroceramics can be made electrically conductive via doping, thus they act as donors or acceptors of electrons. Conductive ceramics such as PbO, RuO_2, In_2O_3, SnO_2, etc. are used as resistive films in microelectronic circuits. Moreso, conductive ceramics are transparent and are widely used for liquid crystal displays (LCDs) on flat screen computer monitors and televisions.

Doped electroceramics can be used in a wide range of sensors and other devices, e.g., thermistors, zirconia oxygen sensors, carbon II oxide gas sensors, solid oxide fuel cells, etc. (Knapp, 2003; Moulson & Herbert, 2003; West, 2014). A thermistor is a variable resistor used as a safety cutout device to prevent overheating. It is found in some toaster ovens. Thermistors also serve as fuel-level sensors in gas tanks. A carbon monoxide gas sensor usually made of SnO_2 ceramics is widely used in chemical laboratories to detect harmful gases among other functions.

Zirconia oxygen sensors are commonly used for automotive engine control devices to reduce emission and fuel consumption. For an automotive engine to work at optimal performance, a specific amount of fuel is required to mix with oxygen. Zirconia oxygen sensor detects the level and amount of air; and prevents high level of air going through the engine.

Solid oxide fuel cells (SOFCs) are devices that convert chemical energy into electricity. They consist of electrodes (comprising of oxygen and fuel) and a doped solid electrolyte, e.g., doped zirconia ceramics. SOFC has a high reliability electricity generation and can be linked to a gas turbine engine.

ix. Thermoelectric Ceramics

Electroceramics are crucial in greener energy generation and supply. For example, improving the electrical conductivity and Seebeck coefficient; and decreasing the thermal conductivity of some electroceramics, e.g., ZnO, $SrTiO_3$, BiCuSeO, $NaCo_2O_4$, etc. (known as thermoelectric ceramics), lead to thermoelements. Thermoelements are n-type and p-type ceramic conductors required for thermoelectric power generation. A thermoelectric power generator (TEG) is a solid state device that converts waste heat (thermal energy) into useable electrical energy (Freer & Powell, 2020;. Iyasara et al., 2020).

The performance of TEG is dependent on the thermoelements. Conventionally, metal alloys (e.g., PbTe, SiGe, etc.) are superior thermoelements compared to doped oxide electroceramics due to their complex structure, high electrical conductivity and enhanced figure of merit (Kieslich et al., 2016; Tian et al., 2014). However, most metal alloys are toxic, scarce, expensive and degrade at high temperatures (Jarman et al., 2013). In contrast, oxide electroceramics are non-toxic, cheap, abundant, possess high melting temperatures , hence potential materials for thermoelectric applications (Funahashi, 2009; Terasaki et al., 1997; Tomeš et al., 2010).

As a result of low energy conversion efficiency associated with TEG when compared to conventional energy generators, it has been constrained to specialised areas (Slack, 1995; Patel & Mehta, 2015; Swapan Chakraborty, 2013) such as :

a. Providing power for cathodic protection systems (internal corrosion control) in gas well casings and pipelines
b. Powering of automotive and deep space explorations
c. Ventilation fans, navigation equipment and landing lights in airports
d. Self-powered systems for wireless data communications.

x. Bioceramics

Bioceramics are electroceramic materials specially designed for use in medicine and dentistry. Though some traditional ceramics are also useful in dentistry. For example, crowns and other artificial dentures made of porcelain fused to metal (Iyasara, Joseph, & Azubuike, 2014). Typical examples of bioceramics include alumina, zirconia, silica, bioactive glass, glass-ceramics, hydroxyapatite, titanium oxide and resorbable calcium phosphates (Nasim et al., 2016).

In orthopedics, bioceramics such as calcium phosphates ceramics, e.g., hydroxyapatite are used for bone replacements in surgeries (Oonishi et al., 2008), while bioceramics composed of
SiO_2 and TiO_2 have shown potential for orthopedic regenerating capabilities (Chen et al., 2019). In dentistry, bioceramics are used for prosthetic dentures, filling bone defects, root repair and for apical retro fills (Nasim et al., 2016).

Generally, bioceramics are desired in medicine and dentistry because of the following qualities (Knapp, 2003):

a. Bioceramics are hard, hence able to withstand fatigue when pulled.
b. They can withstand long-term wear, and do not shrink or swell with temperature or when in liquids.
c. Bioceramics are impermeable to fluids and must not corrode when in contact with body fluids.
d. Bioceramics do not cause allergic reactions and should not be toxic to the body.

xi. Refractory and Abrasive Ceramics

Refractory ceramics are materials with the capacity to withstand high temperatures without degradation, melting or reacting with the environment. They are inert to many fluxing situations, possess reversible thermal expansion and resistance to thermal shocks (Gupta & Kumar, 2004). Refractory ceramics are utilized for furnace linings and typical refractories include high alumina (Al_2O_3 50-80 %), silica -alumina systems (e.g. mullite, Al_2O_3 60-75 %, SiO_2 18-34 %), zircon ($ZrSO_4$), zirconia (ZrO_2), magnetite (MgO 92-98 %, Fe_2O_3 0.1-2 %), Thoria (ThO_2), dolomite (CaO-MgO).

Abrasive ceramics are hard materials which are used to grind, polish and cut softer materials. During abrasion process, abrasive ceramics do not melt even at high temperatures, hence possess high wear resistance and optimum degree of toughness. Typical abrasive ceramics include diamond (the hardest known material with a hardness number of 10 on Mohs scale), silicon carbide, tungsten carbide, alumina, topaz ($SiAl_2Fe_2O_4$), etc.

xii. Superconducting Ceramics

Superconducting (i.e., zero resistance to the flow of current) electroceramics have been developed. $SrTiO_3$ ceramic is the first discovered superconducting ternary oxide ceramic material (Dawson et al., 2013). Because superconducting ceramics' critical temperature, T_C (i.e., the temperature at which the transition occurs from resistivity to superconduction) is much higher than those of conventional metallic superconductors. These ceramic materials are referred to as high T_C-superconductors (high-tech ceramic materials).

High-tech ceramic materials are useful in medicine and drug discovery such as magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR). They are also utilized in magnetic energy storage system, computers, transformers and generators.

3. Conclusions

Clay and related minerals like feldspar are not ceramics but natural ceramic materials for the production of traditional ceramics such as tiles, bricks, sewer pipes, refractories, table wares, etc. With the use of synthetic precursors and improved processing techniques, advanced or modern ceramics are produced. Electroceramic materials are the dominated branch of modern ceramics, hence regarded as the hub of modern technology.

Having x-rayed the applications of electroceramics, viable sectors such as greener energy, telecommunication, electronics and medical will remain dysfunctional without electroceramics. Unfortunately, lack of facilities and adequate power supply in Nigerian tertiary institutions have limited the practical study of ceramic science and engineering to pottery or clay technology.

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