FUNAAB
INAUGURAL LECTURE SERIES

STAINLESS STEELS: A VERSATILE METALLIC MATERIAL IN THE SERVICE OF MAN

By

Professor Peter Olaitan Aiyedun
(Professor of Production Engineering)

Department of Mechanical Engineering College of Engineering (COLENG)
Federal University of Agriculture, Abeokuta, Nigeria.

FUNAAB INAUGURAL LECTURE Series No. 42
Wednesday, 19th June, 2013

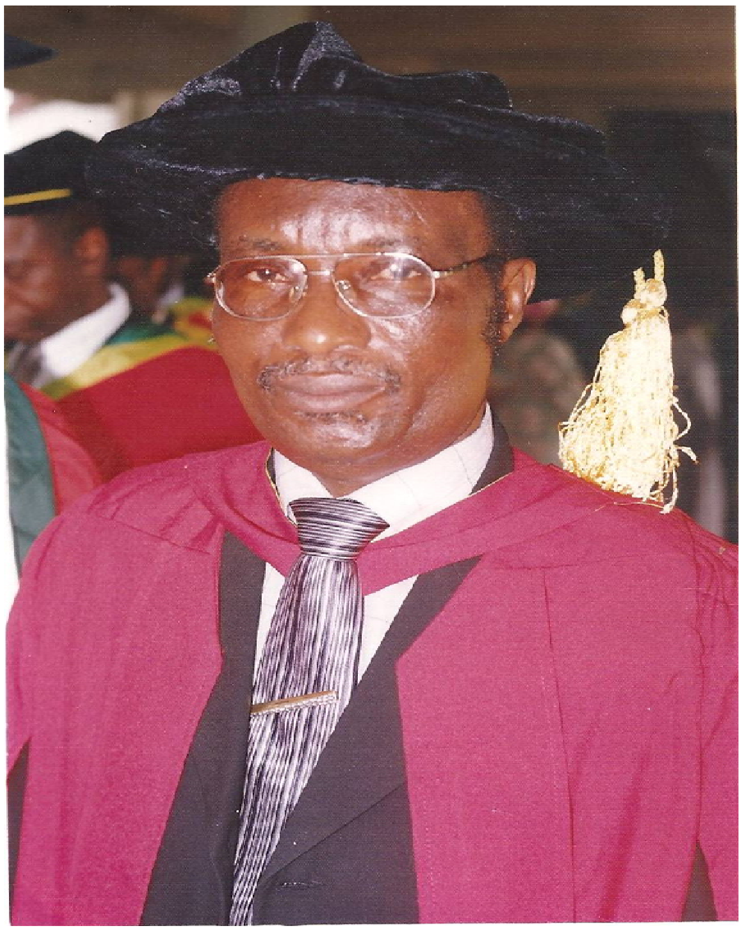
This 42nd Inaugural Lecture was delivered under
the Chairmanship

of

The Vice-Chancellor
Professor Olusola B. Oyewole
B.Sc. (Ife), M.Sc., Ph.D. (Ibadan)

Published 19th June, 2013

ISBN:



Professor Peter Olaitan AIYEDUN
B.Eng. (ABU), M.Sc. (Lond.) DIC, Ph.D. (Sheffield)
FNSE, FMSN, FNIMechE, FNIEM, C.Eng, MIMechE (UK), MINucE (UK)
(Professor of Production Engineering)

DEDICATION

This Inaugural lecture is dedicated to the loving memories of my late father, **Elder Pa Moses Ayanda Aiyedun** and my late mother, **Mrs. Rebecca Abeo Aiyedun.**

STAINLESS STEELS: A VERSATILE METALLIC MATERIAL IN THE SERVICE OF MAN

The Vice-Chancellor,
Deputy Vice-Chancellor (Academic),
Deputy Vice-Chancellor (Development),
Registrar,
Other Principal Officers of the University,
Dean COLENG,
Other Deans and Directors,
Head, Department of Mechanical Engineering,
Members of Senate, and other Colleagues,
My Lords Spiritual and Temporal,
Friends of the University/Special Guests,
Erudite Academics,
Gentlemen of the Press,
Distinguished Ladies and Gentlemen,
Great FUNAABITES.

1.0 OPENING

An inaugural lecture is an address which is given to mark the inauguration or installation of a University Professor at a formal occasion. It is an academic obligation which all persons appointed or promoted professors would be required to fulfill in the course of their career in the University. Indeed, holding an inaugural lecture is imperative in order to confer recognition and respectability on the university professor for the academic subject which he/she professes. Mr. Vice-Chancellor Sir, our distinguished audience, I therefore, give glory to the Almighty God and feel greatly honoured to be given the opportunity to present the 42nd, in the series of inaugural lectures of this great University, the second from the Department of Mechanical Engineering, and the third from the College of Engineering of our frontline University.

Previous inaugural lectures either addressed contemporary issues which are germane to the progress of the society or encapsulate much of the research activities of the lecturer. Some inaugural lectures addressed the academic community on important issues of mutual concern, while some present the progress of activities in a discipline and the manner in which these represent contributions to knowledge and society in general. In my search for topic for this inaugural lecture, the desire to appropriately link Materials Science/Engineering with typical mandate of an Agricultural University was the driving force. On one hand, most of my research works are in this area of Mechanical/Material Engineering. On the other hand, FUNAAB being a specialized University of Agriculture, has nutured to fruition, Mechanical Engineering programme in her bid to fulfill its tripodal mandate of Teaching, Research and Extension Services with overall goal of national self-sufficiency in food production. Mr. Vice-Chancellor Sir, distinguished colleagues, ladies and gentlemen, permit me therefore, to address you on the topic ***"Stainless Steels: A Versatile Metallic Material in the Service of Man".***

2.0 INTRODUCTION

Mr. Vice-Chancellor Sir, may I start by intimating us with the fact that on a typical day, the average modern man is in contact with hundreds of materials; wood, metals, polymers, glasses, ceramics and composites. According to Prof. Adeniyi Afonja in 2002, materials are probably more deep-seated in our culture than most of us realize. Transportation, housing, clothing, communication, recreation, food production, medical care, indeed, virtually every segment of our everyday lives are influenced to one degree or another by materials.

At the initial stages of development, the primary problem was one of selection from a rather limited set of materials, the most appropriate for a given application. The knowledge acquired over the past 60 years or so, has empowered the materials engineer to fashion to a large extent, the characteristics of materials to suit given applications. This has led to the development of tens of thousands of different materials, probably over 50,000 metals and alloys and as many non-metals. Unarguably, the most versatile metallic material is steel.

Steel is an alloy of iron and carbon. It is produced in a two-stage process. First, iron ore is reduced or smelted with coke and limestone in a blast furnace or by the direct reduction process producing molten iron which is either cast into pig iron or carried to the next stage as molten iron. In the second stage, known as steelmaking, impurities, such as, sulfur, phosphorus, and excess carbon are removed and alloying elements for example, manganese, nickel, chromium, vanadium, titanium among others, are added to produce the exact steel required in an Electric Arc Furnace (Fig.1). In the late 19th Century and early 20th Century, the World's largest steel mill was located in Barrow-in-Furness, UK. Today, the world's largest steel mill is in Gwangyang, South Korea. Steel mills turn molten steel into blooms, ingots, slabs, sheets and sections through casting, hot rolling and cold rolling.

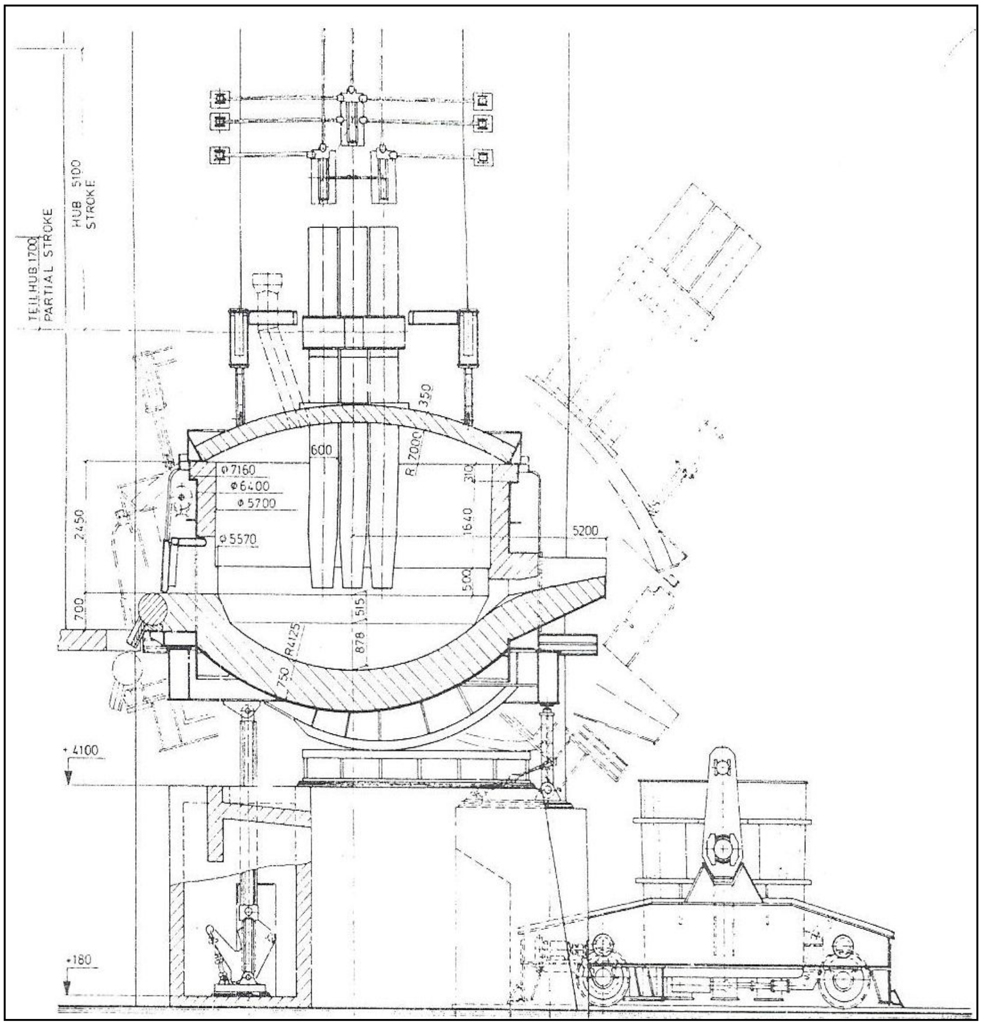


Fig.1: Cross Section of an Electric Arc Furnace. Source: DSC Orientation Course Part 2, 1980

2.1 Steel Development: The Nigeria Experience

2.1.1 History and Development

The history of Steel Development in Nigeria dates back to the pre-independence era. In 1958 initial efforts were made towards the establishment of a metallurgical complex. At that time, action was directed towards the establishment of mini mills that would substitute the limited quantity of imported steel materials which Nigeria was consuming then. As a first step towards this, extensive market surveys were carried out on steel demand and projections were made, it soon became clear that with the already known availability of iron-ore in the Agbaja and Udi areas of the country; it would be more helpful to think in terms of an integrated steel plant. Coal was also available and with the construction of the hydroelectric Kainji Dam, it was expected that electricity would be available in sufficient quantity.

As a result, intensive studies aimed at determining the feasibility of an integrated steel plant were initiated. As these studies were pursued, various international bodies made proposals at various times.

In 1967, a team of Soviet Experts were invited to conduct a feasibility study for setting up an iron and steel plant in Nigeria. The Soviet Experts presented a feasibility report which recommended the use of the blast furnace process for iron making. The report also pointed out that the known iron ore deposits in the country were of poor quality, and recommended that further geological surveys for exploration of better ores and coal for the proposed iron and steel industry should be carried out. This suggestion was carefully examined and it eventually led to the commissioning of Techno-export, an agency of the USSR Government and the Geological Surveys of Nigeria to undertake the job. The agencies were jointly sponsored by the government of the then USSR and Nigeria to carry out aero-magnetic survey of over 22 percent of the country in 1970. Ground magnetic surveys and drilling for suitable types of iron ores and coal followed thereafter.

The investigations revealed that raw materials in reasonable quantity suitable for steel production abound in the country. These include iron ore deposits estimated at over 200 million tons at Itakpe Hill, near Okene, coking coal estimated at 120 million tons at Lafia in Nassarawa State, marble at Jakura and Ubo in Kwara State, Limestone at Mfamosing in Cross River State,. Dolomite at Barum and Osara, and refractory clays at Onibode/Oshiele to mention a few. With these discoveries the basis for setting up a steel plant was established.

To further emphasize government development on the projects, the Nigerian Steel Development Authority (NSDA) was established in April 1971. It had the responsibility for the establishment and the general development of the steel industry in the country as a whole.

In 1973, Messrs Tiajprom-export of the USSR was commissioned to prepare a preliminary project for the establishment of the first Iron ore and steel plant in Nigeria. The report which was submitted in 1974 was rationalized and accepted in 1975. Government specifically accepted the recommendation that the plant should utilize Itakpe Iron Ore and a blend of local and imported coals to produce long steel products only. Also in 1975, government decided that Ajaokuta should be the site for the steel plant and Ajaokuta Steel project as is now known was born.

Mr. Vice-Chancellor Sir, I am happy to inform this gathering that I was fully involved in the Layout and Transportation calculations for Ajaokuta Steel Plant at that time with Tiajprom-export of USSR.

Another bold and giant step for steel development projects was taken in the 1975/80 Development Plan, when the government set up another additional plant based on the direct reduction process that would take advantage of the vast resources of gas which at the time was mostly being flared away. Studies were intensified in this direction and after careful consideration the Direct Reduction process was selected and a site was chosen at Ovwian-Aladja, near Warri. This led to the establishment of the Delta Steel Company which was commissioned in January 1982. Complimentary to the setting up of the Delta Steel plant, government decided to establish rolling mills at three key market centres of the country namely: Oshogbo, Jos and Katsina, with a production capacity for 210,000 tons of steel for each mill per annum. They were commissioned in December 1982.

2.1.2 Inland Rolling Mills in Nigeria

The inland rolling mills in Nigeria are at Katsina, Oshogbo and Jos. The rolling mills were established to manufacture steel products, such as, iron rods, bars and wires using steel billet from the Delta Steel Company. Each of the mills had a capacity for an output of 210,000 metric tons of rolled products per year.

The recorded increases in the capacity utilization of Delta Steel Company positively affected the production levels of the three mills. However, the projects were beset with some constraints. Some of these problems are peculiar to some of the mills, while others are of a general nature. For instance, all the rolling mills experienced a market glut as a result of substantial importation of steel products by major construction firms in the country.

It was generally envisaged that improvement on the facility on ground would be made every 5 years of the preceding phase. But regrettably, there has been no remarkable improvement since the first phase due to poor capacity utilization in virtually all the mills and plants. The poor capacity utilization in the mills was blamed generally on the ensuing economic recession with its attendant exorbitant inflationary rates which partly put developmental constraints on the part of government.

The government at that time promised, however, to continue to explore solutions to these identified constraints within the limit of permissible resources. Consequently, the government opted for the completion of Ajaokuta Steel, the Itakpe - Warri rail line and rehabilitation of Delta Steel, Aladja in the 1997-99 Rolling Plan, as a way to boost steel production. Today, the story is that of reneged promises. Ajaokuta Steel Complex is now fondly referred to as 'Nigeria's number one un-ending white elephant project'.

According to Adelakun (2003), the critical factors that affected the Ajaokuta Steel Plant and the Delta Steel Plant at Aladja are as follows:

1. Poor logistics of supply of raw materials (270 km Itakpe-Ajaokuta rail line)
2. Non-availability of local coking coal for Ajaokuta.
3. Poor quality of Itakpe Iron Ore for Delta Steel Company

operation.

4. Unreliable and high cost of electrical power/energy supply to Delta Steel Company.
5. Lack of facility to produce flat steel products (this presently constitutes 50% of local steel demand).

These two integrated steel plants (Ajaokuta and Delta Steel Plants) need urgent attention for resuscitation.

2.2 Stainless Steel

Stainless steel is the generic name for a number of different steels used primarily because of their resistance to corrosion. A key element they all share is a certain minimum percentage (by mass) of chromium: 10.5%. Although other elements, particularly, nickel and molybdenum, are added to improve corrosion resistance, chromium is always the deciding factor. The vast majority of steel produced in the world is carbon and alloy steel, with the more expensive stainless steels representing a small, but valuable niche in the market.

There are more than 57 stainless steels recognized as standard alloys, in addition to many proprietary alloys produced by different stainless steel producers. These different types of steels are used in an almost endless number of applications and industries: bulk materials handling equipment, building exteriors and roofing, automobile components (exhaust, trim/

decorative parts, engine, chassis, fasteners, tubing for fuel lines), chemical processing plants (scrubbers and heat exchangers), pulp and paper manufacturing, petroleum refining, water supply piping, consumer products, marine and shipbuilding, pollution control, sporting goods (snow skis) and transportation (rail-cars), to name just a few.

Mr. Vice- Chancellor, Sir, the food processing industry is a major beneficiary, in terms of selection of suitable high grade metals for direct contact applications, devoid of metallic contaminants from pitting and corrosion in food systems.

Furthermore, about 200,000 tons of nickel-containing stainless steel is used each year by the food processing industry in North America. It is used in a variety of food handling, storing, cooking, and serving equipment from the beginning of the food collection process through to the end. Beverages such as milk, wine**,** beer, soft drinks and fruit juice are processed in stainless steel equipment. Stainless steel is also used in commercial cookers, pasteurizers, transfer bins, and other specialized equipment. Advantages include easy cleaning, good corrosion resistance, durability, economy, food flavor protection, and sanitary design. The petrol chemical industry also depends on enormous use of stainless steel materials for the construction of major equipment to meet international specifications/ standards.

Stainless steels come in several types depending on their microstructure. Austenitic stainless steels contain at least 6 percent nickel and austenite-carbon containing iron with a face-centered cubic structure and have good corrosion resistance and high ductility (the ability of the material to bend without breaking). Ferritic stainless steels (ferrite has a body-centered cubic structure) have better resistance to stress corrosion than austenitic, but they are difficult to weld. Martensitic stainless steels contain iron having a needle-like structure.

Duplex stainless steels, which generally contain equal amounts of ferrite and austenite, provide better resistance to pitting and crevice corrosion in most environments. They also have superior resistance to cracking due to chloride stress corrosion, and they are about twice as strong as the common austenitics. Therefore, duplex stainless steels are widely used in the chemical industry in refineries, gas-processing plants, pulp and paper plants, and sea water piping installations.

2.2.1 Raw Materials

Stainless steels are made of some of the basic elements found in the earth: iron ore, chromium, silicon, nickel, carbon, nitrogen, and manganese. Properties of the final alloy are tailored by varying the amounts of these elements. Nitrogen, for instance, improves tensile properties like ductility. It also improves corrosion resistance, which makes it valuable for use in duplex stainless steels.

2.2.2 The Manufacturing Process

The manufacture of stainless steel involves a series of processes. First, the steel is melted, and then cast into solid form (Fig. 2).

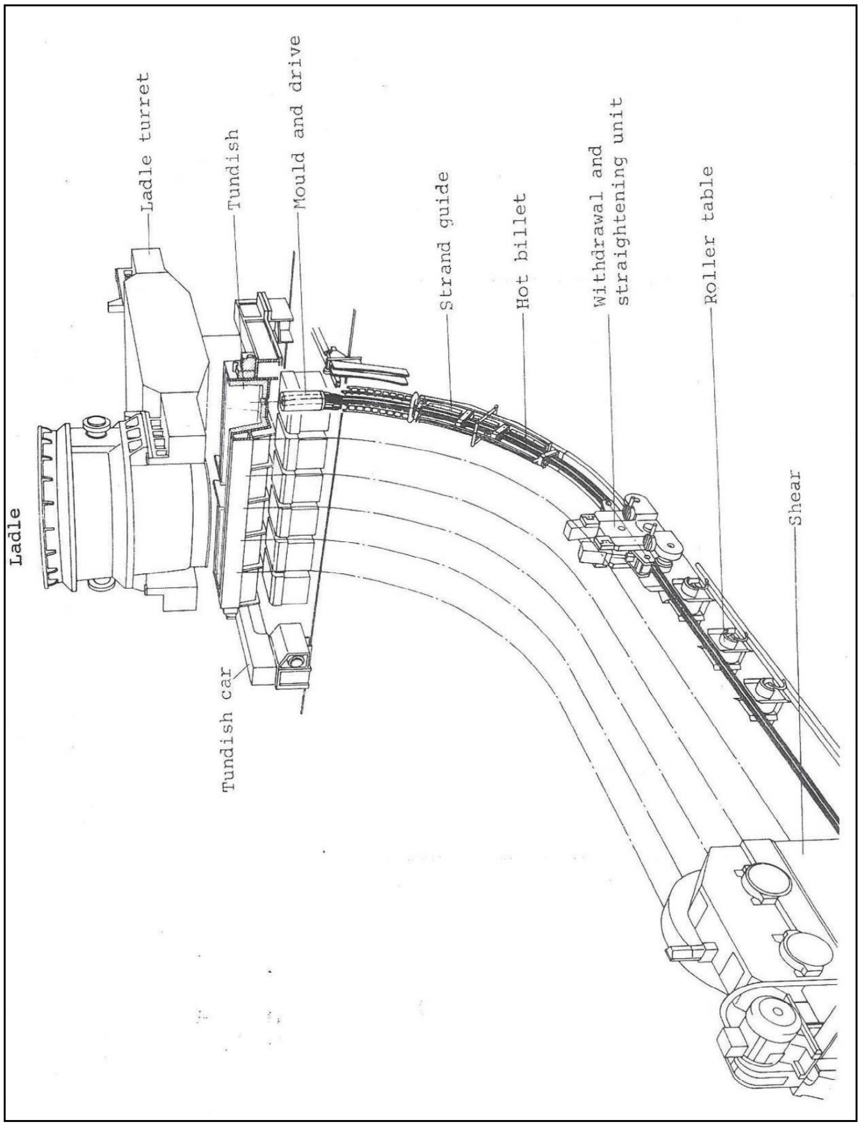


Fig. 2: Six strand continuous casting machine. Source: DSC Orientation Course Part 2, 1980

2.2.3 Melting and casting

The raw materials are first melted together in an electric furnace. This step usually requires 8 to 12 hours of intense heat. When the melting is finished, the molten steel is cast into semi-finished forms. These include blooms (rectangular shapes), billets (round or square shapes 3.8 centimeters in thickness), slabs, rods, and tubes.

2.2.4 Forming

The semi-finished steel goes through forming operations, beginning with hot rolling, in which the steel is heated and passed through huge rolls. Blooms and billets are formed into bar and wire, while slabs are formed into plates, strips, and sheets. Bars are available in all grades and come in rounds, squares, octagons, or hexagons of 0.63 cm in size. Wire is usually available up to 1.27 cm in diameter or size. Plate is more than 0.47cm thick and over 25.4cm wide. Strip is less than 0.47cm thick and less than 61cm wide. Sheet is less than 0.47cm thick and more than 61cm wide.

After various forming steps, the stainless steel is heat treated and then cleaned and polished to give it the desired finish. Next, it is packaged and sent to manufacturers, who weld and join the steel to produce the desired shapes.

2.3 The Unique Advantage of Stainless Steel

For a wide variety of applications, stainless steel competes with carbon steels supplied with protective coatings, as well as other metals such as aluminium, brass and bronze. The success of stainless steel is based on the fact that it has one unique advantage. The chromium in the stainless steel has a great affinity for oxygen, and will form on the surface of the steel at a molecular level as a film of chromium oxide. The film itself is about 130 Angstroms in thickness; one Angstrom being one millionth of one centimetre. This is like a tall building being protected from the rain by a roof similar to the thickness of one sheet of ordinary copy paper. This layer is described as passive, tenacious and self renewing. Passive means that it does not react or influence other materials; tenacious means that it clings to the layer of steel and is not transferred elsewhere; self renewing means that if damaged or forcibly removed more chromium from the steel will be exposed to the air and form more chromium oxide.

This means that over a period of years, a stainless steel knife can literally be worn away by daily use and by being re-sharpened on a sharpening stone and will still remain stainless. Silver plated cutlery will eventually wear through to the base alloy, but stainless steel cutlery cannot wear through. Manhole and access covers in the water treatment and chemical industry are widely made out of both galvanized steel and stainless steel. In normal use, galvanized steel can last many years without corrosion occurring and in these cases there would be little advantage apart from aesthetic reasons to switch to stainless steel. Where stainless steel comes into its own is where the galvanized coating is constantly being worn away, for example by conveyor chains being dragged over it, or constantly being walked over, or where very corrosive chemicals are being randomly splashed onto it. This leads on to the important point that the initial investment cost of producing a component or fabrication in stainless steel will tend to be more expensive than using ordinary steel, not just because of the higher cost of stainless steel, but also because it is more difficult to machine. However, it is the better life-cycle-costs of stainless steel that makes it attractive, both in terms of much longer service life, less maintenance costs, and high scrap value on de-commissioning.

2.4 The Development of Stainless Steel

The inventor of stainless steel, Harry Brearley, was born in Sheffield, England in 1871. Mr. Vice-Chancellor sir, I wish to state that to the glory of God, it was from this same city that I obtained my Ph.D., precisely twenty-nine years ago. Harry Brearley's father was a steel melter, and after a childhood of considerable hardship, he left school at the age of twelve to get a job washing bottles in a chemical laboratory. By years of private study and night school, he became an expert in the analysis of steel and its production. Having already established his reputation for solving metallurgical problems, Brearley was given the opportunity in 1908 to set up the Brown Firth Laboratories, which was financed by the two leading Sheffield steel companies of the day. This was a highly innovative idea of its time and opened up problem-solving research steel production.

In 1912, Brearley was asked to help in solving specific problems encountered by a small arms manufacturer, whereby, the internal diameter of rifle barrels was eroding away too quickly because of the action of heating and the destructive effect of discharge gases. Brearley was, therefore, looking for steel with better resistance to erosion, and not corrosion. As a line of investigation he decided to experiment with steels containing chromium, as these were known to have a higher melting point than ordinary steels. Chromium steels were already at that time being used for valves in aero engines. Iron has an atomic weight of 56, chromium 52, so chromium steel valves are lighter than their carbon steel counterparts, another reason why they were adopted so quickly by the emerging aircraft industry. Using first the crucible process, and then more successfully an electric furnace, a number of different melts of 6 to 15% chromium with varying carbon contents were made. The first true stainless steel was melted on the 13th August, 1913 (100 years ago). It contained 0.24% carbon and 12.8%

chromium. Brearley at this time was still trying to find more wear-resistant steel, and in order to examine the grain structure of the steel, he needed to etch (attack with acid) samples before examining them under the microscope. The etching reagents he used were based on nitric acid, and he found that this new steel strongly resisted chemical attack. He then exposed samples to vinegar and other food acids, such as, lemon juice and found the same result.

At this time, table cutlery was silver or nickel plated. Cutting knives were of carbon steel which had to be thoroughly washed and dried after use, and even then rust stains would have to be rubbed off using carborundum stones. Brearley immediately saw how this new steel could revolutionize the cutlery industry; then one of the biggest employers in Sheffield, had great difficulty convincing his more conservative employers. On his own initiative, he had knives made at a local cutler's, R.F. Mosley. To begin with, Brearley referred to his invention as 'rustless steel'. It was Ernest Stuart, the cutlery manager of Mosley who first referred to the new knives as 'stainless' following his experiments in which he failed to stain them with vinegar. 'Corrosion resisting' steel would really be the better term, as ordinary stainless steels do suffer corrosion in the long term in hostile environment. Other claims have been made for the first invention of stainless steel, based upon published experimental papers that indicated the passive layer corrosion resistance of chromium steel or patented steels with a 9% chromium content intended for engineering purposes. Since Brearley's contribution came from purely empirical conclusions, he immediately seized on the practical uses of the new material. Within a year of Brearley's discovery, Krupp in Germany was experimenting by adding nickel to the melt. Brearley's steel could only be supplied in the hardened and tempered condition; the Krupp steel was more resistant to acids, was softer and more ductile and therefore easier to work. There is no doubt that without Brearley's chance discovery, the metallurgists at Krupp would have also made the discovery themselves. From these two inventions, just before the First World War, were the development of the '400' series of martensitic and '300' series of austenitic stainless steels.

The First World War largely put a halt to the development of stainless steel, but in the early 1920s a whole variety of chromium and nickel combinations were tried including 20/6, 17/7 and 15/11. Brearley's successor at the Brown Firth Laboratories was Dr W.H. Hatfield, who was credited with the invention in 1924 of 18/8 stainless steel (18% chromium, 8% nickel) which with various additions, is still dominating the melting of stainless steel today. Dr Hatfield also invented 18/8 stainless with titanium added, now known as 321. Prof. C.M. Sellars (one of my Ph.D supervisors) delivered the 50^{th} Hatfield Memorial Lecture in the University of Sheffield, U.K. in

1995, and he has worked extensively on deformations and hot working processes of metals at elevated temperatures (Sellars *et al* 1976, Sellars 1981, Sellars 1984, Aiyedun *et al* 1997, Aiyedun and Sellars, 1998).

Most of the standard grades still in use today were invented in the period 1913 to 1935, in Britain, Germany, America and France. Once these standard grades became accepted, the emphasis changed to finding cheaper, mass-production methods, and popularising the use of stainless steel as a concept. This tended to stifle the development of new grades. However, after the Second World War, new grades with a better weight-to-strength ratio were required for jet aircraft, which led to the development of the precipitation hardening grades such as 17:4 PH. From the 1970s onwards, the duplex stainless steels began to be developed. These have far greater corrosion resistance and strength than the grades developed in the 1920s and are really the future for the increasing use of stainless steel.

2.5 Product Characteristics

Stainless steel can be selected for use compared to other materials for a number of different reasons, apart from its resistance to corrosion. These include:

- Its aesthetic qualities: it can be polished to a satin or mirror finish.
- 'Dry Corrosion' occurs in steel at higher tempera-

tures, where, it oxidizes or scales up. Stainless steel is far more resistant to this than ordinary carbon steel and other grades, such as, 310 (25% chromium 20% nickel) were specifically developed for use at high temperatures.

- Non-contamination of the liquids stainless steel comes in contact with, since there is no coating to break down and dissolve.
- Weight savings: as thinner sections can be used, more innovative design structures are made possible, with cost savings on foundations and platform weights.
- Many anti-corrosion coatings are fire hazards or the materials themselves have low melting points.

2.6 Applications

2.6.1 *Cutlery: Applications*

The most everyday use of stainless steel is obviously in cutlery. Very cheap cutlery is made out of grades 409 and 430, with the finest Sheffield cutlery using specially produced 410 and 420 for the knives and grade 304 (18/8 stainless steel, 18% chromium 8% nickel) for the spoons and forks. For example, the grade 410/420 can be hardened and tempered so that the knife blades will take a sharp edge, whereas, the more ductile 18/8 stainless is easier to work and, therefore, more suitable for objects that have to undergo numerous shaping, buffing and grinding processes.

2.6.2 *Stainless Steel in the Food Industry:*
Stainless steel is the preferred general use metal for food contact surfaces because of its corrosion resistance and durability in most food applications, (Table.1). This table shows the various grades of stainless steels used in the diary industry. Type 303 stainless steel is similar to both 304 and 316 grades of stainless steel. Its corrosion resistance is similar to 304 but not as resistant as type 316 which also has higher sulphur content, thus, allowing easier machining than 304 and 316 grades. Hence, type 303 is used for such items like shafts, gears, threaded uses, aircraft fittings and bushings.

Type 304 stainless steel is the most widely used grade, for example in milk, beer and wine production. The grade is used to produce springs, fasteners, such as, nuts and bolts. It is used in water and mining industry for filters and screens. It has wide architectural uses for trim, hand rails, kitchen wares, such as, sinks, refrigerators, food preparation tables and table wares. Type 304 is used for mildly corrosive chemicals.

Type 316 stainless steel has 10-18% chromium, 11-14% nickel and a minimum of 2% molybdenum. Molybdenum gives 316 additional resistance to corrosion making it useful in chemically hostile conditions. Thus, it is used widely in most corrosive conditions, such as food and beverage processing, chemical processing, agricultural uses and the pulp and paper industry. The lower carbon grade type 316L (which allows easier welding) is used for marine applications.

Requirements for materials in contact with food fall into the following categories:

1. Chemical, bacteriological and organoleptic neutrality with regard to the food product.
2. Ability to be cleaned such that the hygiene and appearance of the product is guaranteed.
3. Durability, including resistance to corrosion and aging.

Stainless steel meets all these requirements and it has other factors like its mechanical characteristics, expansion coefficient, thermal conductivity and ease of use.

Table 1: Grades of stainless steel used for different equipment in the dairy industry

Equipment	End use	Steel Grade
Refrigerated storage tank	All dairy products	304
Centrifuge pasteurizer	Milk, yoghurt, cream, butter	304, 316
Plate and tubular heat exchangers	Milk, cheese, cream, butter, yoghurt	316
Packaging machine	Milk, cream, yoghurt	316
Ultrafiltration equipment	Cheese	316
Maturation tank	Cheese, ice cream, cream, butter	304, 316
Cheese racks	Cheese	304
Other equipment	All dairy products	304, 316

Source: ISSF 2010 (www.worldstainless.org)

Stainless steels have a smooth, neutral surface which does not pick up tastes or smells. They are extremely strong and can withstand tough industrial environments. They are easy to clean, disinfect and does not react with lactic acids formed by fermenting food products.

One of the great advantages of stainless steel is that it imparts no taste to the food that it comes into contact with. This has created one interesting anomaly. Traditional wine making uses barrels of oak. The newer wine-producing nations use very large vats and storage containers of stainless steel as this gives them far greater economics of scale. However, in conventional wine making, the acid of the wine dissolves some of the wood to give an 'oak' body taste. Thus, when stainless steel vats are used, oak chips are deliberately put into the vats to create the same effect in order to satisfy traditional wine drinkers.

2.6.3 *Other uses of Steel By-product in Agriculture:*
Steel slag is currently being used as fertilizer, soil conditioners and recovery of metal values. Slag composition is mainly CaO, MgO, SiO_2, MnO and other valuable micronutrients, such as, copper, zinc, boron and cobalt.
Calcium and magnesium compounds improve soil pH (because of their basicity). There are also plant nutrients and stabilizers for soil aggregates.

Silicate of slag mineral is useful for plant nutrition and soil quality. It provides beneficial effects on plant health and soil structure, increase phosphate mobility in the soil and the efficiency of phosphate fertilization (Rex, 2002). The pumping and containment of oils, gases and acids have created a large market for stainless steel tanks, pipes, pumps and valves. The storage of dilute nitric acid was one of the first major success stories for 18/8 stainless steel as it could be used in thinner sections and was more robust than other materials. Special grades of stainless steel have been developed to have greater corrosion resistance. These are used in de-salination plants, sewage plants, offshore oil rigs, harbour supports and ships propellers.

2.6.4 *Architecture:*

Architecture is a growing market. Many modern buildings use stainless steel for cladding. When reinforced concrete first started to be used, it was considered that the carbon steel used would not rust as cement, obviously derived from limestone, is alkaline. However, constantly using grit salt on bridges can change the pH to acidic, thereby, rusting the steel which expands and cracks the concrete. Stainless steel reinforcing bar, although initially expensive, is proving to have very good life cycle costing. The low maintenance cost and anti-vandal characteristics of stainless steel provide a growing market in public transport, ticket machines and street furniture.

2.6.5 *Nuclear Power Industry:*

The nuclear power industry uses large quantities of stainless steel, often specified with low cobalt content, for both power generation and radiation containment. Special louvered ventilation shafts are made, which are designed to be used in emergencies to seal off plants for years if necessary. Nuclear fuel rods are also clad with stainless steel, 316. Steam and gas turbines use stainless steel because of its corrosion resistance and heat resisting qualities.

2.6.6 *Medicine:*

In medicine, especially clean melted stainless steel is used for medical implants and artificial hips. A great deal of medical equipment - such as orthopedic beds, cabinets and medication examination machines, cadaver tables, dental equipment are made to conform with International standard from stainless steel because of their hygienic and easy to clean qualities. Pharmaceutical companies also use stainless steel for pill funnels and hoppers and for piping creams and solutions.

2.6.7 *Automobile Industry:*

In the automobile industry, there is increasing use of stainless steel in the production of cars, primarily for exhaust systems (grade 409) and catalytic converters, and also for structural purposes.

With greater attention being paid to achieving low long-term maintenance costs, less environmental degradation effects and greater concern for life cycle costs, the market for stainless steel continues to improve.

3.0 MY CONTRIBUTIONS

3.1 Overview

Mr. Vice-Chancellor sir, the main focus of my research work has been on hot rolling (flat and rod) of steels at various strain rates and reductions. In this major aspect, I have explored hot flat rolling simulation using the Sims theory, Bland and Ford's cold rolling theory; temperature effects and changes at low strain rates and low reductions; strength of High Carbon SS316 by torsion, plane strain compression and rolling; yield stress variation and micro-hardness across thickness; effects of roll chilling and geometrical factors on load and torque of steels; influence of composition on strength and microstructure of hot rolled HCSS316 (High Carbon Stainless Steel) and LCSS316 (Low Carbon Stainless Steel); spread effects and friction when steels are hot rolled at low strain rates and low reductions; microstructural changes during and after hot rolling of HCSS316.

The research has led to further work on reverse sandwich effects in hot flat rolled HCSS316; development of Reverse Sandwich Model (RSM) based on Afonja and Sansome (1973);

and an integration of the reverse sandwich model into the hot rolling Bland and Ford's theory for load and torque calculations. For rod rolling, the "phantom roll method" was applied while simulation of load and torque for C-Mn steels and HCSS316 were obtained.

Since 2005, when I joined FUNAAB, and based on the Agricultural focus of this University and the geological nature of Abeokuta and its environs, my research focus shifted to non-metallic materials research, i.e. Ceramic materials, characterization of kaolinite clays of this area and their possible usage for production of bricks, stonewares, porcelain tiles, water filters, etc; Evaluation of corrosion performance of metallic materials in some selected media, viz: cassava mesh, maize pulp and sea water; process simulation and mechanical design of distillation unit of a bioethanol plant using cassava as feed stock.

Other areas of research that are still being worked on are integrated steel plants, environmental engineering aspects and layout requirement, energy studies, viz: energy efficiency of industries, such as, mineral bottling companies, beverages, flour mills, wire and cable industries as well as solar energy studies, solar water heaters and solar distillation units, noise studies and design of a highway side retractable shrub/grass cutter.

3.2 Sims Theory for Hot Rolling and Bland & Ford's Theory for Cold Rolling

3.2.1 Excess Load and Torque in Hot Rolling

The advent of continuous casters with in-line rolling has led to difficulties associated with hot rolling at low reduction (<10%) and low strain rates (0.01-1.5)s^{-1} which are not encountered under normal hot rolling conditions (strain rates of 1.5-500s^{-1}). Excessive load and torque in comparison to values obtained by normal rolling practice are experienced at these low strain rates and low reductions.

Extensive literature exists on yield strength, temperature, and structural changes during and after hot working and their effects on rolling load and torque. In particular, the calculation method due to Sims and Bland and Ford's were studied.

In Sims theory for hot rolling and for wide strip rolling, the specific roll load, P and torque, T are estimated from Equations (1) and (2):

$$P = \int_{0}^{\phi_N} S^{+} R d\theta + \int_{\phi_N}^{\alpha} S^{-} R d\theta \qquad (1)$$

$$T = 2R_0 R^{/} \bar{k} \left[\int_{0}^{\phi_N} \frac{S^{+}}{k} \theta d\theta + \int_{\phi_N}^{\alpha} \frac{S^{-}}{k} \theta d\theta \right] \qquad (2)$$

where:

- α - angle of entry (i.e. maximum value of q), radians
- k - instantaneous yield stress, N/mm^2
- q - angle subtended by a point on roll surface with respect to the line joining roll centres, radians
- Φ_N - Neutral angle, radians
- R^1 - deformed roll radius, mm
- R_0 - undeformed roll radius, mm
- s - normal roll pressure N/mm^2

These equations are based on Orowan's result for compression of plastic slab between rough inclined plates, Von Karman equation and a number of assumptions due to Sims (Afonja and Sansome,1973; Aiyedun, 1984; Aiyedun, 1986; Aiyedun *et al.*, 1997).

The Bland and Ford's theory (BF) is a cold rolling theory, where, sliding takes place throughout the arc of contact. It has, however, been found to be applicable to a hot rolling situation, where, sliding exists throughout the roll gap. This is the situation for hot rolling of HCSS316 at rolling temperatures of 900°C – 1200°C; reductions of 0 – 15%; strain rates of 0.07 – 1.5s^{-1}; and geometrical factor of 4.0 – 20.00 as reported in the literature (Aiyedun, 1984; Aiyedun, 1986; Aiyedun *et al.*, 1997; Aiyedun and Sellars, 1998).

Roll load, P and roll torque, T are, respectively, given by equations (3) and (4);

$$P = R^{/}\left\{\int_{0}^{\phi_N} S^{+} d\theta + \int_{\phi_N}^{\alpha} S^{-} d\theta\right\} \quad (3)$$

$$T = 2R_0 R^{/}\int_{0}^{\alpha} S\theta d\theta \quad (4)$$

where,

$$S^{+} = \bar{k}.N.\frac{h}{h_2}.e^{\mu H} \quad (5)$$

$$S^{-} = \bar{k}.N.\frac{h}{h_1}.e^{\mu(H_1 - H)} \tag{6}$$

$$H = 2\sqrt{\frac{R^{/}}{h_2}}.\tan^{-1}\sqrt{\frac{R^{/}}{h_2}}.\theta \tag{7}$$

$$\frac{h}{h_2} = \frac{R^{/}}{h_2}.\theta^2 + 1 \tag{8}$$

$$\frac{h}{h_1} = \left(\frac{R^{/}}{h_2}.\theta^2 + 1\right)(1 - r) \tag{9}$$

where h, h_1, h_2 = height, $h_1$and h_2 are at entry and exit
r = reduction, N= Neutral angle

Based upon an earlier approach of Sparling (El-Kalay and Sparling, 1968), which dealt with a mixed sliding-sticking situation in hot flat rolling, another model called Hot Rolling Bland and Ford (HRBF) was developed by me which was used to calculate mean yield stress during rolling and this has been used to calculate rolling load and torque at low strain rates under sliding condition (Aiyedun, 1984; Aiyedun, 1986).

3.2.2 Temperature for Hot Rolling Load and Torque Calculation

In rolling processes generally, it is vital to know the temperature distribution within the slab. Reports abound in the literature (Aiyedun *et al.*, 1997, Serajzadeh *et al.*, 2002) that temperature is the dominant parameter controlling the kinetics of metallurgical transformations and the flow stress of the rolled metal. The mean temperature $\bar{T}_m$ used by Aiyedun (1984) in HRBF was determined as:

$$\bar{T}_m = \frac{1}{2}\left(\bar{T}_1 + \bar{T}_2\right) \qquad (10)$$

where T_1 and T_2 are entry and exit temperatures.
The true yield stresses for load $\bar{k}_p$ and torque $\bar{k}_g$ calculation were respectively given as equations (11) and (12):

$$\bar{k}_p = \frac{1}{\alpha}\int_0^{\alpha} k d\theta \qquad (11)$$

$$\bar{k}_g = \frac{1}{r}\int_0^{r} kde = \frac{2}{\alpha^2}\int_0^{r} k\theta d\theta \qquad (12)$$

$$e = \frac{h_0 - h}{h_0} \qquad (13)$$

where:, r = reduction

Hot torsion tests were carried out on a High Carbon SS316 (with Nb , V and Ti) in the temperature range (600-1200)°C and strain rate range of $(3.6x10^{-3}$-$1.4)s^{-1}$ to obtain the hot strength data for the rolling conditions. Experimental hot rolling loads and torque from two laboratory mills for a 10% reduction and at low strain rates $(0.08\text{-}1.5)s^{-1}$ were compared with calculated values obtained by the two methods of calculation methods due to Sims and Bland and Ford's Theory for rolling load and torque, which adequately took into account the temperature variations during roll contact. Other materials, viz: lead, aluminium alloy, mild steel , medium carbon SS316, and a specially cast Low Carbon SS316 were also hot rolled using analogous conditions to those for the High Carbon SS316.

Mr. Vice-Chancellor sir, this work was carried out in the world acclaimed "Steel City; Sheffield" at the University of Sheffield, United Kingdom.

The results have shown that for hot flat rolling of High Carbon SS316 at low reduction (<10%) and low strain rates (0.08-1.5)s^{-1}, the following factors were the main contributors to the observed excess load and torque.

(a) Roll chilling effects are important at low rolling speeds, so using the mean entry temperature as the mean rolling temperature gives (15-25%) excess load and torque experimentally compared with calculated value (5-10%) excess for industrial rolling conditions;
(b) Temperature gradients leading to a higher strength of the surface layer of the slab compared with the bulk cause underestimation of rolling load and torque by (5-15%) for both experimental and industrial rolling conditions; and
(c) In materials where dynamic precipitation occurs during deformation, the combined effects of temperature gradients, and precipitation strengthening, is about 5 to 25% experimentally or in practice.

However, structural changes during and after deformation have also highlighted the important effects of composition and thermal history of a material when predicting hot rolling load and torque at low strain rates.

3.3 Reverse Sandwich Model (RSM) based on Afonja & Sansome's Work and its Integration into hot rolling bland & Ford's Theory

Stemming from the works of Afonja and Sansome (1973) on Sandwich rolling of hard metals, I developed a Reverse Sandwich Model (RSM) for Calculating Rolling Load and Torque for Steel (HC SS316) in 2003.

The RSM predicts rolling load and torque at low strain rates and low reductions with due consideration for temperature, yield stresses and Zener-Hollomon parameter variations along the thickness which had been sub-divided into 17 zones. Comparison of the model's result with experimental values gave mean errors of 4.42%, 19.6% and 6.4% for mean temperatures, load yield stress and torque yield stress, respectively (Aiyedun and Shobowale, 2003).

3.3.1 Temperature Effects / Changes

A finite difference (2-D) model developed to describe the heat flow at low strain rates (0.08-1.5s^{-1}) and low reduction (<10%) for a hot flat rolled slab both during air cooling and during roll contact has been used in conjunction with experimentally measured temperatures through specimen thickness during roll contact after reheating to temperatures in the range 1000-1200^{0}C for mild steel, LCSS316, and HCSS316 (with Nb,Vand Ti). At high strain rates (>1.5s^{-1}), a steep temperature gradient was produced in the specimen near the surface whereas for low strain rates ($\approx 0.08s^{-1}$), this temperature gradient penetrated deep into the thickness leading to a large drop in the mean rolling temperature (Fig. 3).

Roll chilling, leading to higher values of Zener-Holloman parameter, Z, resulted from a decrease in the mean rolling temperature and the large temperature gradient during roll contact (Fig.4). Temperature changes due to material composition, reheating temperature, contact time and rolling conditions led to precipitation strengthening and roll chilling effects which accounted for the excess load and torque observed experimentally and in industrial processes.

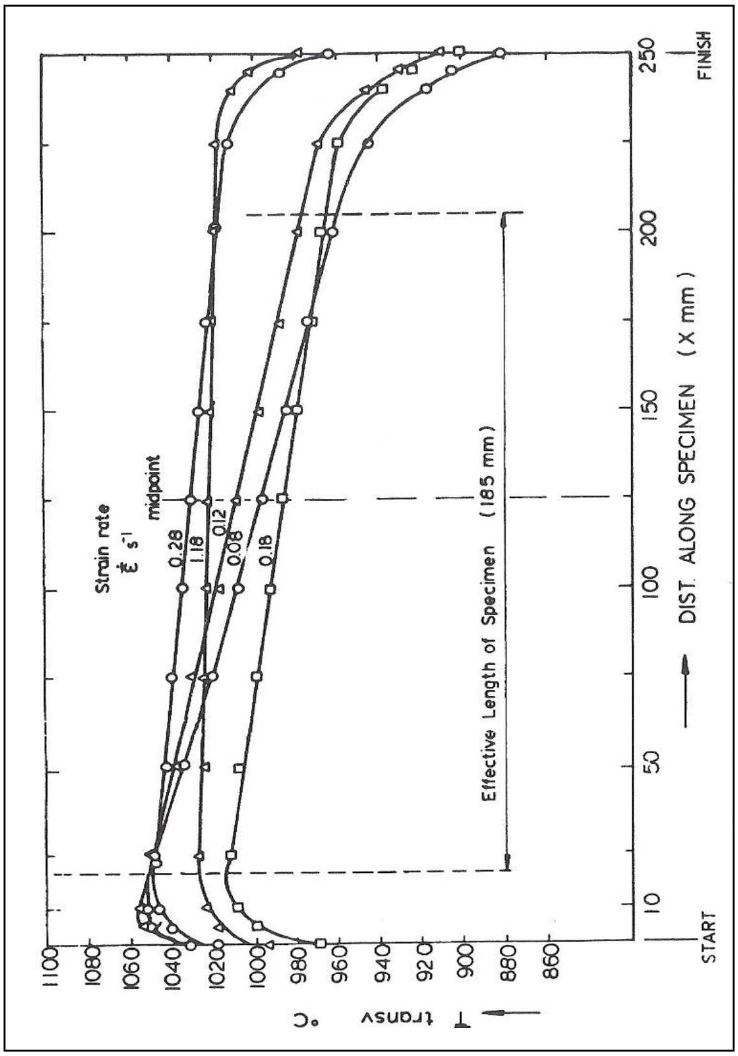


Fig. 3: Plot of T_{transv}(^{0}C) versus distance along specimen (x mm) during rolling at different strain rates for $T_f \sim 1050^0$C and r ~ 10% .

Source: Aiyedun *et al.*, 1997

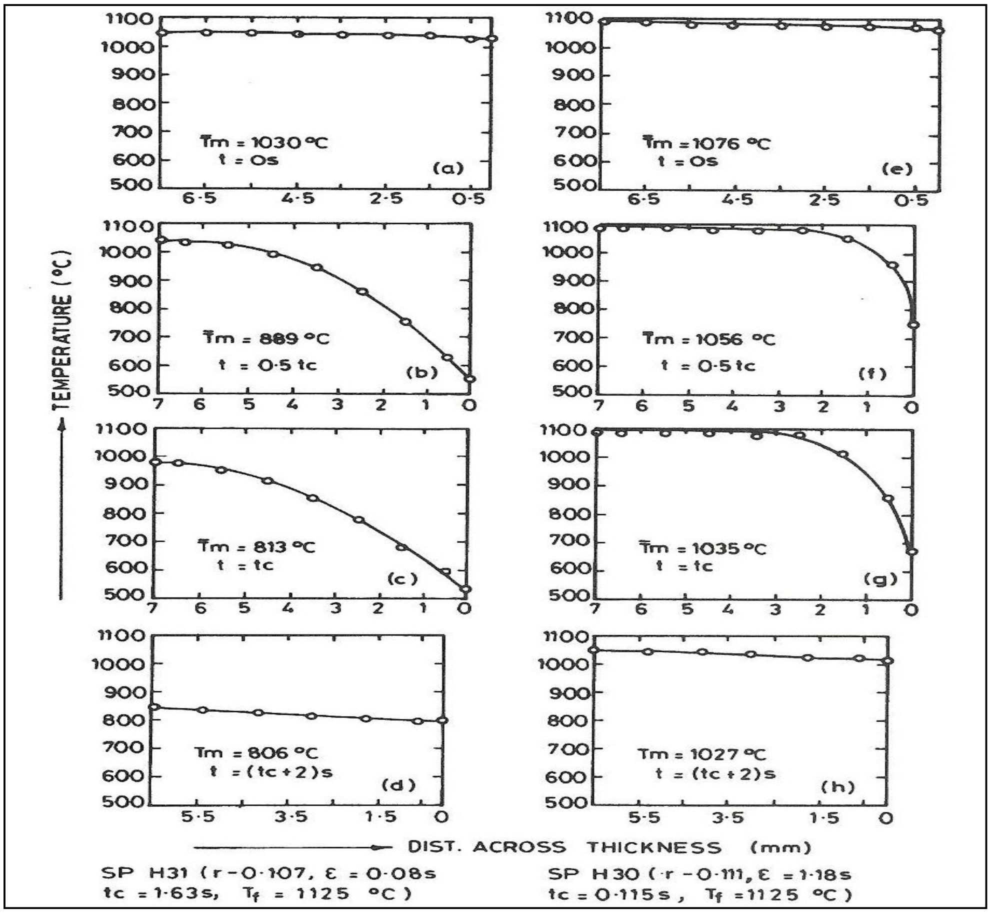


Fig. 4: Temperature across thickness for HCSS316 hot rolled at slow and fast strain rates on mill A at different times during and after roll contact (T_f ~ 1125^{0}C, r ~ 10%).

Source: Aiyedun *et al.*, 1997

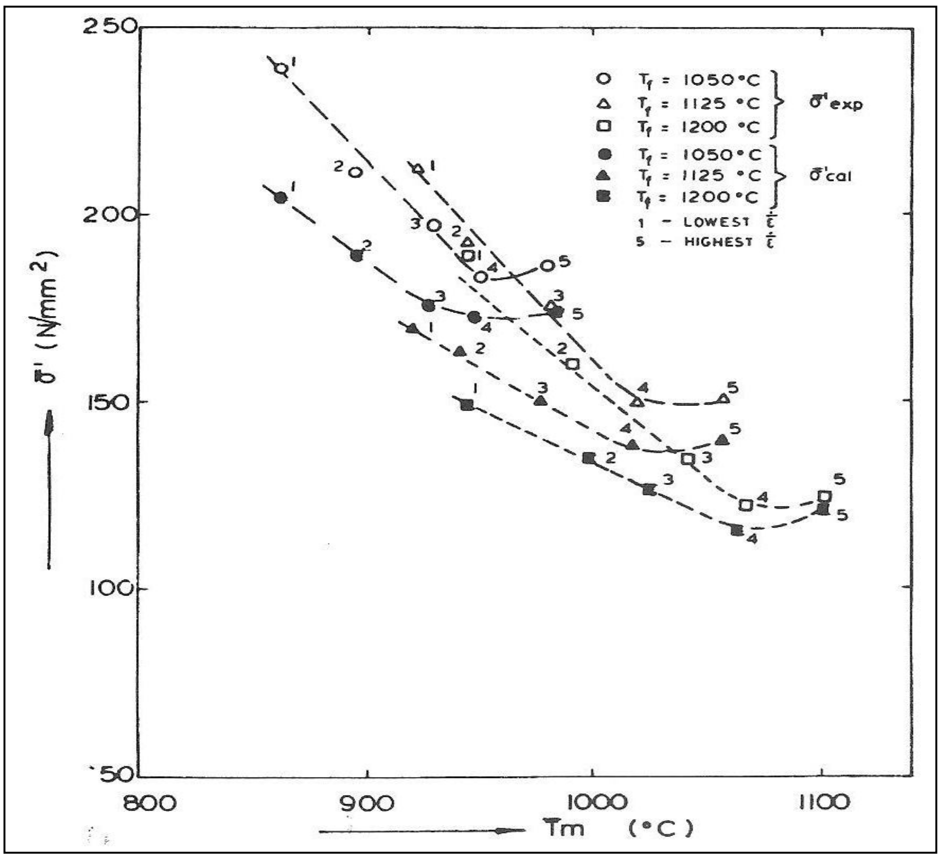


Fig. 5: Plot of uniaxial flow stress, experimental and calculated, versus mean rolling temperature for r = 10% reduction, hot rolling on mill A (with different T_f and varying speeds for HCSS316).

Source: Aiyedun *et al*., 1997

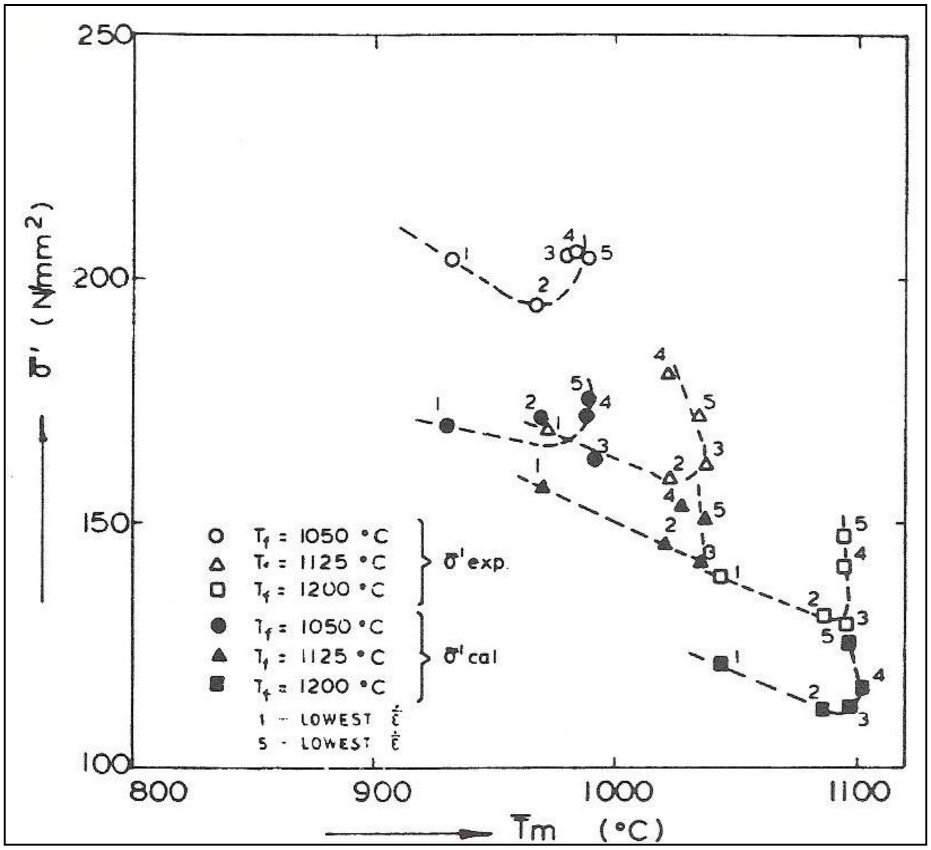


Fig. 6: Plot of uniaxial flow stress, experimental and calculated, versus mean rolling temperature for r = 10% reduction, hot rolling on mill B (with different T_f and varying speeds for HCSS316).

Source: Aiyedun *et al.,* 1997

Further work on the best mean rolling temperature by Aiyedun and Aliu (2009) showed that at low strain rates, Hot Rolling Bland and Ford's theory (HRBF) gave closer approximations to experimental results (Figs. 5&6). The harmonic mean was found to give the best mean rolling temperature for hot flat rolling simulation at low strain rates in comparison to geometric mean, arithmetic mean, and root mean square as shown in Fig.7.

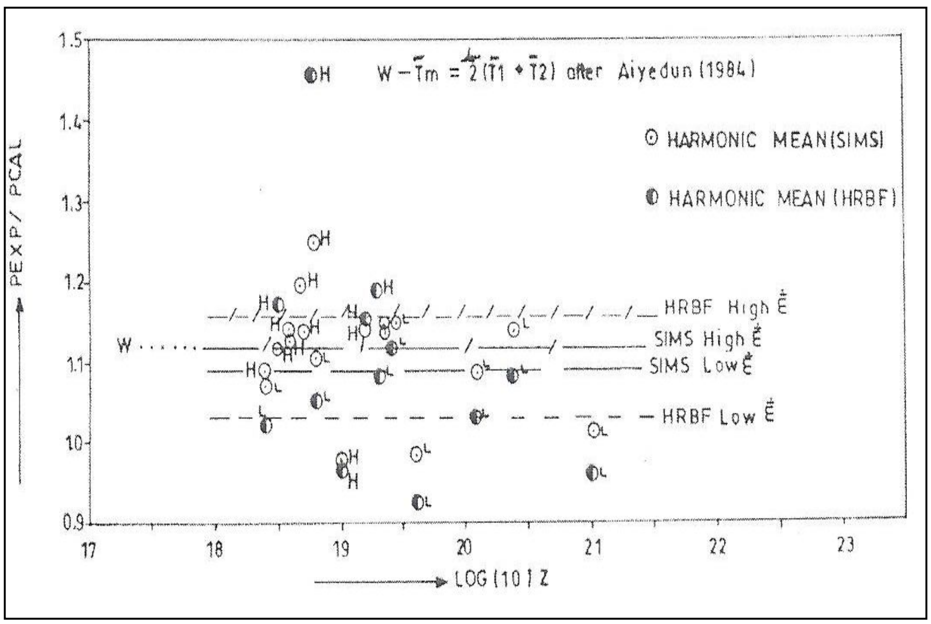


Fig. 7: Load variation with $Log_{10}Z$ for Sims and Bland and Ford's (HRBF) Methods using Harmonic Mean Temp (HM).
Source: Aiyedun and Aliu, 2008

3.3.2 Load and Torque Calculations

Computation of hot flat rolling load and torque using Sims theory which was based on sticking throughout the roll gap and a second theoretical simulation method known as HRBF (Hot Rolling Program using Bland and Ford's cold rolling theory) were used to obtain rolling load and torque for HCSS316. These were compared with experimental values obtained for hot flat rolling on two laboratory mills A and B of roll diameters 254.0 mm and 139.7 mm, respectively, for steels (HCSS316) rolled at temperatures of 600-1200^{0}C, reduction of less than 15% and strain rates of (0.01-1.5)s^{-1} according to Aiyedun (1986) and Alamu *et al.*, (2009).

A third and new theoretical method called the Reverse Sandwich Model (RSM) was developed by me in 2003. It was based on the temperature, yield stresses and Zener-Holloman's parameter variations along the thickness applied in calculating rolling load and torque. The following far reaching results were obtained. For hot flat rolling of HCSS316 at strain rates (0.08-1.5)s^{-1} and low reductions (<10%), theoretical and experimental results obtained have shown that the Reverse Sandwich Model (RSM) theory as well as the Hot Rolling Bland and Ford's (HRBF) theory can be used to predict accurately rolling load and torque. The loads and torque predicted agree with those obtained by using Sims theory on both mills A and B.

For hot rolling on mill B, the systematic decrease in P_{exp}/P_{cal} and T_{exp}/T_{cal} as $\log_{10}Z$ increased, observed for all the three theories on mill A was not observed. P_{exp}/P_{cal} for all the three theories had a random scatter with change in $\log_{10}Z$.

A mean $(P_{exp}/P_{cal})_{SIMS}$: $(P_{exp}/P_{cal})_{B\&F}$: $(P_{exp}/P_{cal})_{RSM}$ was 1.20: 1.22: 1.27 respectively. (Aiyedun, 1984; Aiyedun, 1986; Aiyedun and Shobowale, 2003) as shown in figures 8 to 10.

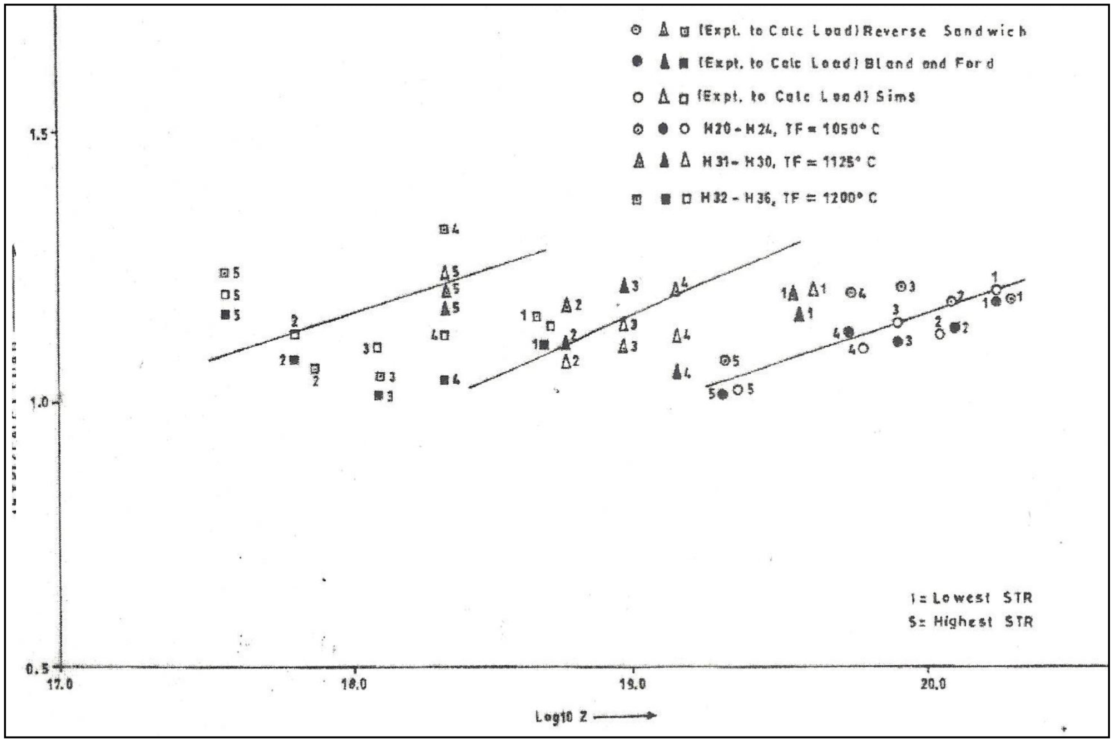


Fig. 8: Graph comparing the Reverse Sandwich, Sims, Bland and Ford's Theories for the ratio of experimental to calculated load for HCSS316 hot flat rolled on mill A, r≈10%, T_f and STR variable.

Source: Aiyedun, 2004

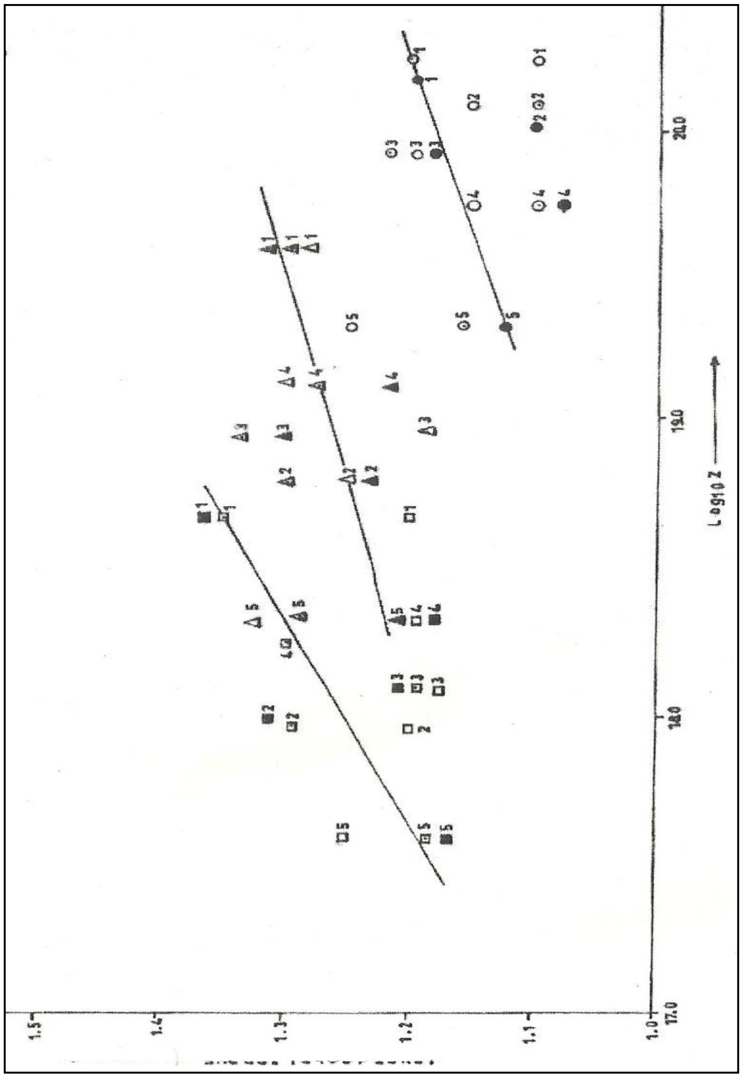


Fig. 9: Graph comparing the Reverse Sandwich, Sims, Bland and Ford's Theories for the ratio of experimental to calculated torque for HCSS316 hot flat rolled on mill A, r≈10%, T_f and STR variable.

Source: Aiyedun, 2004

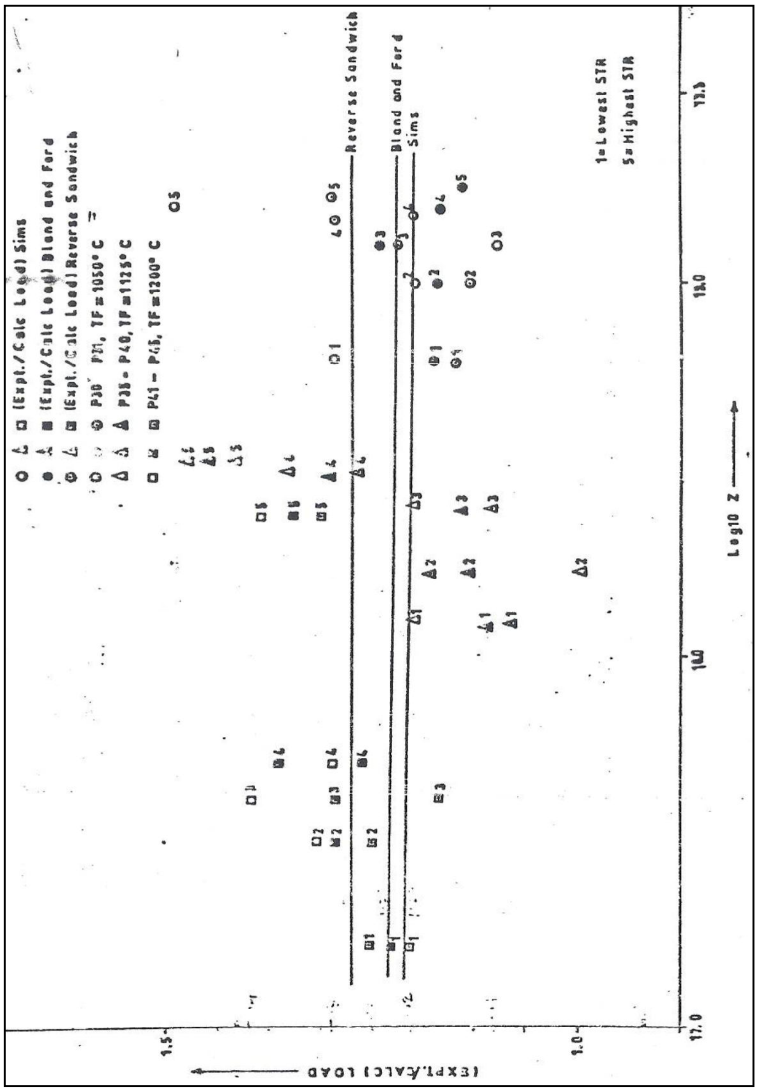


Fig. 10: Graph comparing the Reverse Sandwich, Sims, Bland and Ford's Theories for the ratio of experimental to calculated load for HCSS316 hot flat rolled on mill B, r≈10%, T_f and STR variable.

Source: Aiyedun, 2004

3.3.3. Yield Strength for Hot Rolling of Stainless Steel.

Aiyedun (1999), proposed a new method of estimating the material mean yield strength for use in the calculation of rolling load and torque for HCSS316 steels hot rolled at low reduction and low strain rates. The method combined the temperature, strain, strain rates as well as the composition effects and was obtained from equations based on hot torsion isothermal tests under similar conditions. The surface third element across thickness has a strain increase of ≈15%, Zener-Holloman parameter, Z increase of $\approx 1x10^4$ and a decrease of $\approx 250^0C$ in the rolling temperature, T_m. This corresponded to an increase of $\approx 200Nmm^{-2}$ in the yield strength of the surface element and an increase of ≈35% in the material mean yield strength. This was found to be due to the effects of temperature, composition and rolling condition.

An almost 3 times increase in yield strength of the surface material confirm the reverse sandwich (or roll chilling) effects for hot flat rolling at low strain rates (Figures 11 to 13) .

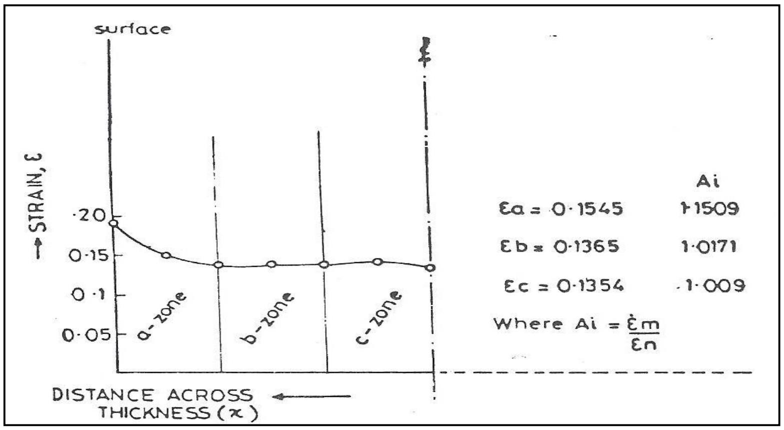


Fig. 11: Strain profile across zone a,b,c of thickness.
Source: Aiyedun, 2009

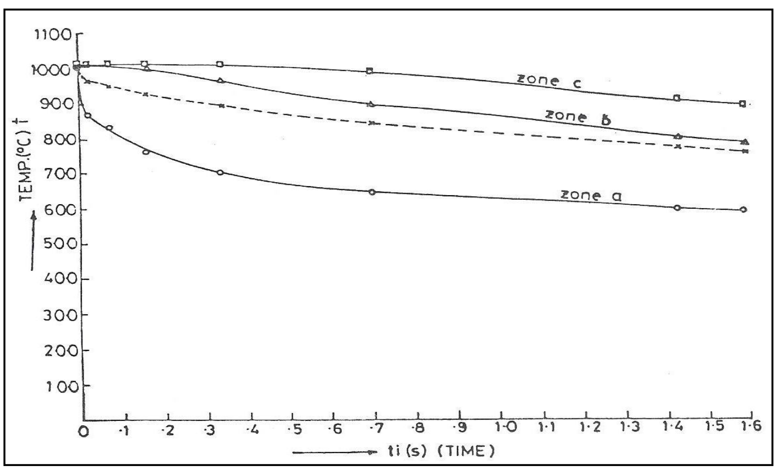


Fig. 12: Temperature profile in zone a, b, c during roll contact.
Source: Aiyedun, 2009

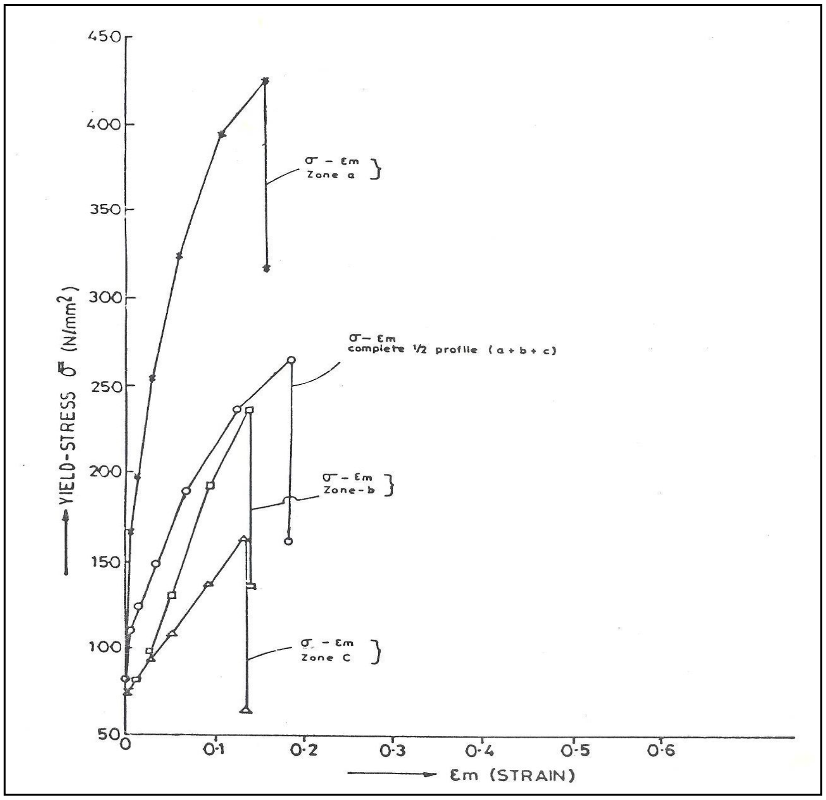


Fig. 13: Stress-Strain (σ-ε_m) curves for zones a, b and c for complete 1/2 profile of SR during roll contact.

Source: Aiyedun, 2009

Torsional test data and plain strain compression data for various stainless steel materials (AISI 316SS, AISI 316L, AISI 304 and HCSS316) were analyzed and a relationship describing their yield strength as a function of their deformation variables (strain rate and temperature) was obtained. Stress-Strain data obtained were transformed using a FORTRAN programming language to generate stress-strain equations, and consequently the yield stress and yield strength due to load and torque for different materials were determined. The yield strength values obtained when plotted against $Log_{10}Z$ by starting from specific values of Zener-Holloman parameter (Z) and rising to a peak before decreasing to a specific value (for that due to load and torque) as shown in Figures 14 and 15.

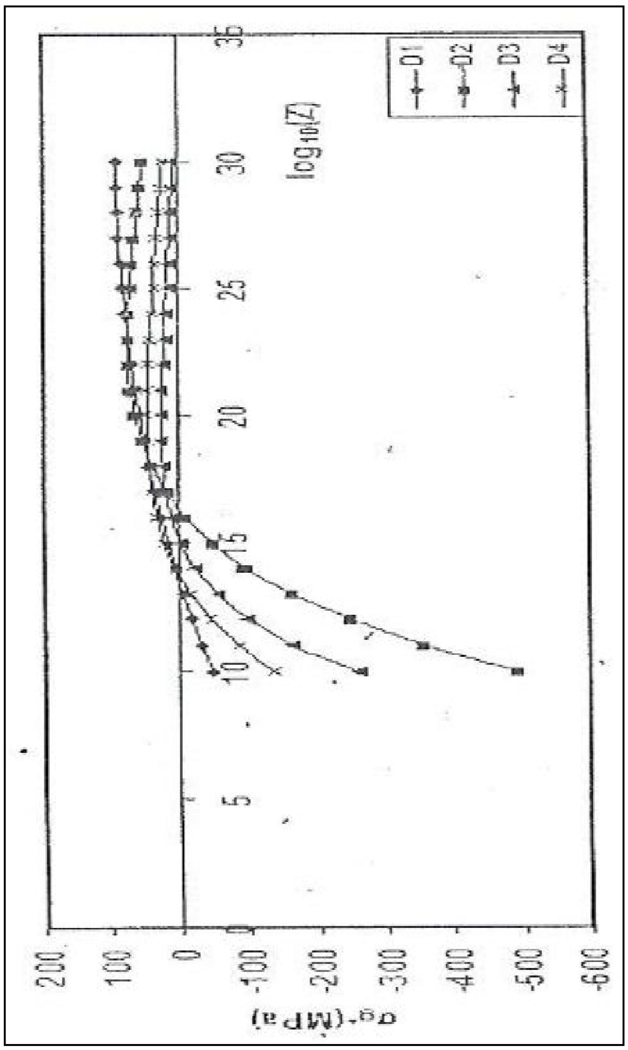


Fig. 14: Dependence of the Yield Strength due to load on the Zener-Hollomonparameter.
Source: Aiyedun *et al.*, 2010

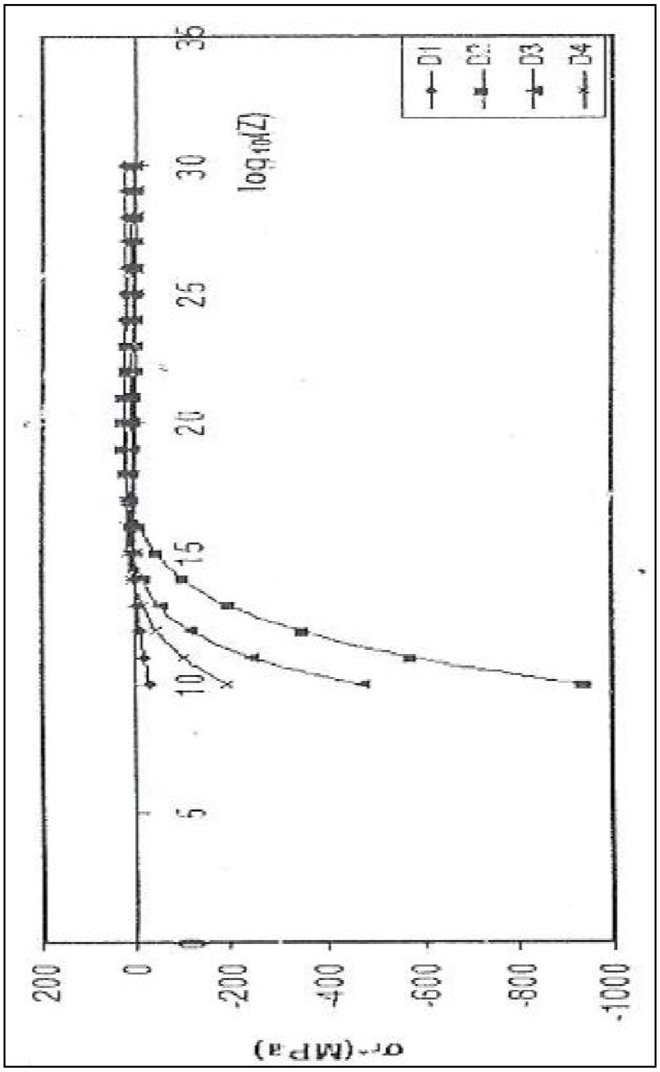


Fig. 15: Dependence of the Yield Strength due to torque on the Zener-Hollomon parameter.
Source: Aiyedun *et al.*, 2010

3.3.4 Effects of Geometric Factors on Rolling Characteristics

The effects of geometric factors, viz: deformed radius to final thickness ratio, R^1/h_2; width to thickness ratio, w_1/h_1; rolling reduction, r, and furnace temperature, T_f: on roll force and torque of HCSS316 hot flat rolled at low strain rates and low reduction were investigated. Results showed that for a geometric ratio of $R^1/h_2 \approx 9.30$ and $w_1/h_1 \approx 4.7$, as strain rate decreased from 1.2 to $0.08s^{-1}$, P_{exp}/P_{cal} and T_{exp}/T_{cal} increased on mill A while their values were constant on mill B, where, $R^1/h_2 \approx 5.0$ for the same conditions of w_1/h_1 value. Similar trends were observed for different reheating temperatures of 1050^0C, 1125^0C, and 1200^0C. As reheating temperature increased from 1050^0C to 1200^0C, the observed excess load and torque at lowest strain rates increased from 1.13 to 1.23 and 1.20 to 1.37, respectively, on mill A. The minimum yield stresses observed on both mills correspond to a particular strain rate which was inversely proportional to the geometric factor, R^1/h_2 while the work also confirmed the uneven sharing of the rolling torque with one roll carrying 80% of the total torque according to Aiyedun (1997), Aiyedun (2001) and Alamu and Aiyedun (2003).

3.3.5. Effect of Fine Precipitates on strength and Micro-hardness across thickness.

It will be worthwhile within the little time at my disposal in this lecture to mention briefly that modest contribution was made to the frontier of knowledge in my research on the effects of fine precipitates on the strength of HCSS316 hot rolled at low reductions and low strain rates (Aiyedun and Sellars, 1998); micro hardness across thickness for stainless steel hot rolled at low strain rates and reduction (Aiyedun, 1997). Fine precipitates of Nb(C,N) and V(C,N) of sizes 25-50nm were found to increase flow stress in laboratory scale rolling and industrial hot rolling by up to 25%, while the reverse sandwich (roll chilling) effect and precipitation strengthening effect were found to account for all excess load and torque obtained when steels with additions of Niobium, Vanadium, Titanium, etc, hot rolled at low strain and low strain rates with each effect accounting for 15 and 25%, respectively (Aiyedun and Sellars, 1998). Optical and electron microscopy were used to confirm the presence of these fine precipitates while the micro hardness results confirmed the temperature effect in terms of roll chilling (reverse sandwich) effect in LCSS316 (Aiyedun, 1997) as shown in Fig. 16.

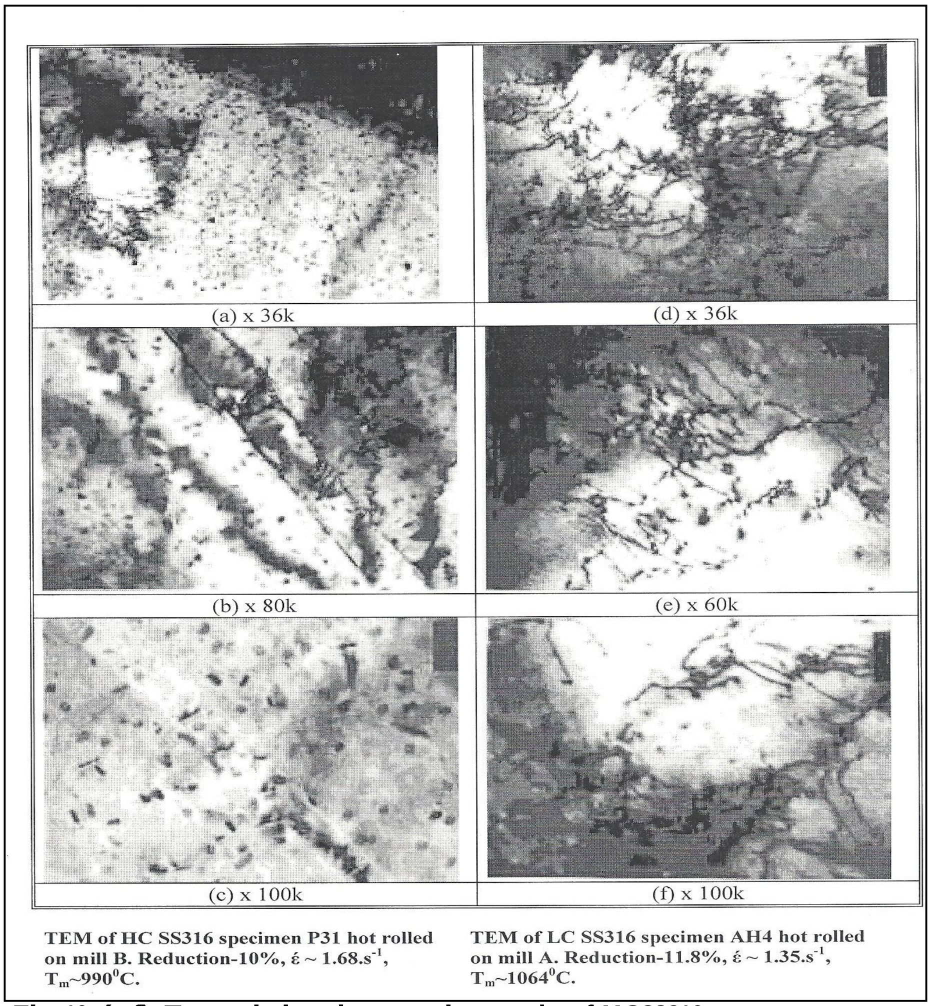


Fig. 16: (a-f): Transmission electron micrographs of HCSS316 and LCSS316 showing fine precipitates of Nb(C,N) and V(C,N) for HCSS316 and no precipitates for LCSS316.

Source: Aiyedun, 2006a

3.3.6 Influence of Composition on Strength and Microstructure of Rolled HCSS316 and LCSS316

In my research on stainless steel, microstructural considerations were not left out. When HCSS316 (with Nb, V and Ti) and LCSS316 (without Nb, V and Ti) were hot rolled at low reductions and low strain rates, both V and Nb present in HCSS316 inhibit dynamic recrystallization with the steel exhibiting a pronounced resistance to both dynamic and static recrystallization. Very fine Nb(C, N) and V(C, N) particles produced at low strain rates (0.08 – 1.5)s^{-1} in HCSS316 (as confirmed by transmission electron micrograph) led to precipitation strengthening, while these particles and strengthening were absent in LCSS316 (with negligible Nb, V and Ti). The percentage precipitation strengthening in HCSS316 hot rolled at furnace temperatures of 1200^{o}C and 1050^{o}C on mill A (diameter 254mm) at low strain rate of $\approx 0.08 s^{-1}$ and high strain rate of 1.12 – 1.27s^{-1} were quantified to be 20% and 34%; and 6% and 8%, respectively, while for mill B (diameter 139.7mm), at low strain rate of 0.17 – 0.22s^{-1} and high strain rate of 1.68 – 1.77s^{-1}, there was a constant strengthening increase of 18% and 20% (Aiyedun, 2006a).

3.3.7 Microstructural Changes During and After Hot Rolling of HCSS316

Further on microstructural study, High carbon stainless steel 316 (with Nb, V, and Ti) was hot flat rolled on mills of diameters 139 mm and 254 mm at rolling temperatures of 600 – 1200^0 C, reduction of 10% and strain rates of 0.08 – 2.5s^{-1}. The decreased strain rate allowed more time for precipitation to occur during deformation in steels which contain carbide and nitride forming elements, thus, reducing the recrystallization rate. Using the Scanning Electron Microscope (SEM) and the Transmission Electron Microscope at high magnification of 36,000 – 100,000 confirmed the presence of fine precipitates of Nb(C,N) and V(C,N) in HCSS316 hot flat rolled at low reductions (r~10% and low strain rates (0.01 – 2.0)s^{-1} (Fig.16c). The faster precipitation of carbides and nitrides in steels was due to higher solution treatment temperatures and higher carbon content. The presence of Nb, V and Ti in stainless steels also showed the possibility of the formation of their precipitates either dynamically or statically during deformation at low strain rates. This influenced the dynamic recovery and recrystallization rates and, hence, an increase in its hot strength. Thus, strengthening increases with dynamic straining and longer time of contact (Aiyedun, 2006b).

Earlier in 2002, I delivered a paper at the Nigerian Materials Congress (NIMACON-2002) on Spread Calculation for Stainless Steel (HCSS316) Hot Flat Rolled at Low Strain Rates during a discourse on Engineering Materials and National Development (Aiyedun, 2002). Results obtained which were based on further development of empirical equations as developed by El-Kalay and Sparling (1968), were quite novel and significant for hot flat rolling of stainless steel at low strain rates (Aiyedun, 2002).

3.4 Simulation of Rod Rolling

Mr. Vice-Chancellor, Sir, distinguished scholars here present, highlight of my scholarly contribution in stainless steel research is not limited to flat rolling alone; to the glory of God, I have equally recorded modest contributions in rod rolling.

3.4.1. Simulation of Load and Torque during Rod Rolling of HCSS316 at Low Strain Rate

Flat rolling is a process in which a work-piece of constant thickness enters a set of rolls and exit as a product with different constant thickness using flat rolls. Form rolling or shape rolling is a rolling method for products, such as, **I**-beam, channels, railroad tracks and large diameter pipes and rods using grooved rolls (Schaffer *et al*., 1999) but for rod rolling, grooved and flat rolls are used.

In some of my research work in this area, rolling loads of HCSS316 for seventeen sequential passes for the reduction of a 125 x 125 mm^2 billet to a 16 mm diameter rod at four different starting mean temperatures of 988, 1094, 1095 and 1191^0C and at different strain rates of 0.4, 0.8, 1.2 and 1.6 s^{-1}, respectively, were simulated using the "Phantom Roll" method for HCSS316. In general, it was observed that load value increased as starting temperature decreased and for each set of starting temperatures, the load value increased with temperature (Fig.17). In all cases, the load values for grooved rolls were higher than those for flat rolls. Similar results obtained for load were also obtained for torque. The abnormal behaviour obtained for load or torque versus $Log_{10}Z$ at highest rolling temperature of 1191^0C could be that due to recrystallization and, hence, recovery never fully took place during rolling at this temperature, thereby resulting in strain localization (Fig.18). An inverse relationship exists between strain rate and load, and strain rate and torque. (Aiyedun *et al.*, 2008; Aiyedun *et al*., 2011).

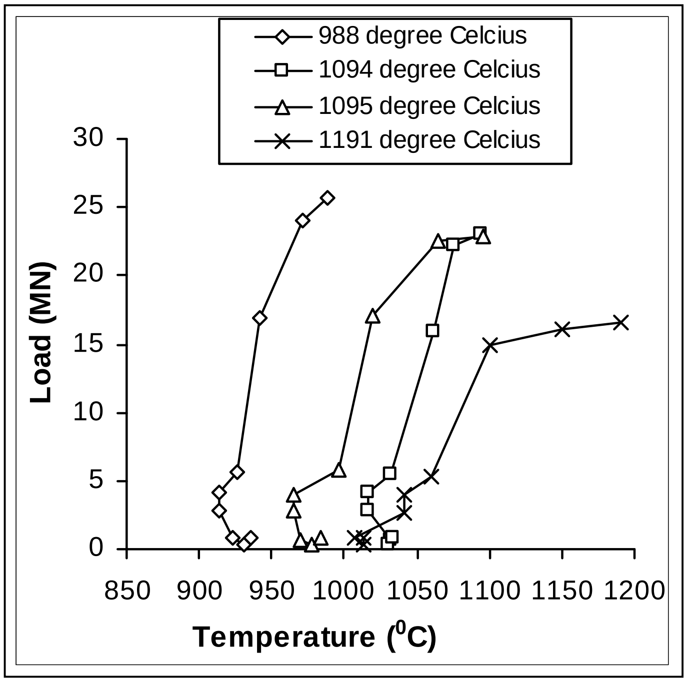


Fig. 17: Plot of load versus temperature for rolling using flat rolls at initial starting strain rate of 0.4s-1 for four mean temperatures.

Source: Aiyedun *et al.*, 2008

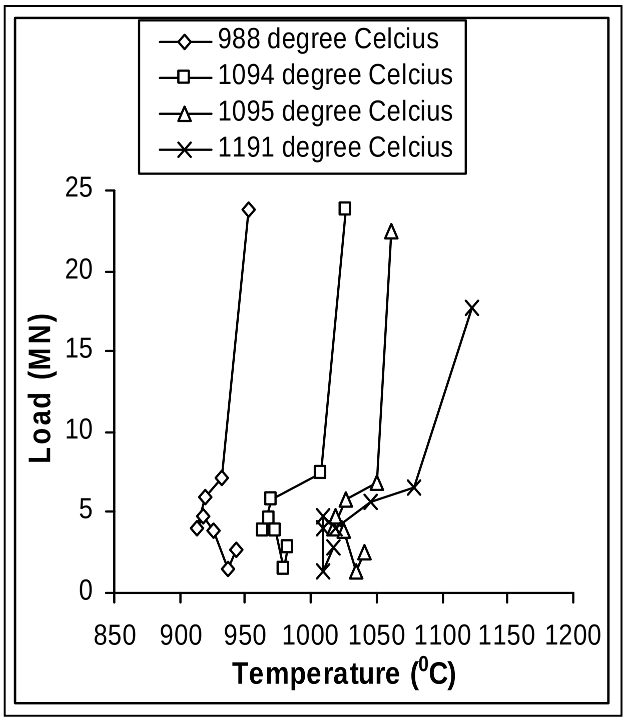


Fig. 18: Plot of load versus temperature for rolling using grooved rolls at initial starting strain rate of $0.4s^{-1}$ for four mean temperatures.

Source: Aiyedun *et al.*, 2008

3.4.2. Simulation of Load and Torque during Rod Rolling of Carbon-Manganese Steel Using the "Phantom Roll" Method

Further on rod rolling, simulation of rolling load for a 17 pass, 125 x 125 mm carbon manganese steel billet hot rolled to a 16 mm diameter rod was carried out, and published in the Akamai University Journal in the United States (Aiyedun *et al.*, 2011). Load calculations were obtained using the temperature values for rod rolling obtained by the "Phantom Roll" method. Investigations were carried out for four different starting mean rolling temperatures between 900-1200^{0}C, and four different rolling strain rates of 0.8, 0.4, 1.2 and 1.6s^{-1}. Results obtained showed that for all cases, rolling in grooved rolls required more power (higher load) compared to rolling in flat rolls. Loads were higher for lower rolling temperatures for both flat rolls and grooved rolls. An increase in rolling speed also corresponded to an increase in load for both grooved and flat rolls. Straight-line equations fitted load against $\log_{10}Z$ (where Z is Zener-Hollomon's Parameter) at temperatures of 988, 1094 and 1095^{0}C while two straight lines fitted the highest temperature of 1191^{0}C in checking the combined effect of temperature and strain rate on load. This abnormal behaviour was attributed to strain localization in two distinct zones caused by recrystallization and incomplete recovery during working at the highest temperature of 1191^{0}C. Similar results were obtained for torque simulation during rod rolling of C-Mn steel (Aiyedun and Oseghale, 2008; Aiyedun *et al.*, 2011).

3.4.3. Other Areas of My Research since 2005

Since joining FUNAAB as a Professor of Production Engineering in November 2005, the focus of my research shifted slightly to Investigation and Characterization of some clay deposits of Abeokuta, South West, Nigeria; Evaluation of Corrosion Performance of Metallic Materials in some selected media; Process Simulation and Mechanical Design of Distillation Unit of Bio-ethanol Plant using Cassava as Feedstock; Development of Pulp and Paper using stem and fruit stem of *musa species*, etc. These noble efforts have produced three (3) Ph.Ds and several M.Eng. Post-graduates, while others are still under supervision. Efforts from these joint researches have produced publications of over fifteen (15) journal articles and conference proceedings. Table.2 also shows a typical chemical analysis of Abeokuta clays compared to some other international kaolinitic clays.

Table 2: Chemical Analysis of various clays

(Murray, 1986)				Olokode and Aiyedun (2011)	
Component (%)	Middle Georgia (Cretaceous)	East Georgia (Tertiary)	English kaolin	Abeokuta (Fajol)	Abeokuta (Ajebo 2)
SiO2	45.30	44.00	46.77	78.30	68.60
Al2O3	38.38	39.50	37.79	9.10	20.50
Fe2O3	0.30	1.13	0.56	2.94	0.16
TiO2	1.44	2.43	0.02	0.87	1.75
MgO	0.05	0.03	0.24	0.31	0.09
CaO	0.25	0.03	0.13	0.26	=
Na2O	0.27	0.08	0.05	0.24	0.07
K2O	0.04	0.06	1.49	1.01	0.01
L.O.I.	13.97	13.90	12.79	6.92	8.82
MnO	-	-	-	0.02	-
P2O5	-	-	-	0.03	-

Source: Prasad *et al.* (1991); Olokode and Aiyedun, (2011) For the twelve (12) samples of five (5) clays around Abeokuta which were investigated, SiO_2 ranged between 46.40-78.30% while Al_2O_3 was between 9.10-34.00%, as reported by Olokode and Aiyedun (2011), Prasad *et al.* (1991), Olokode *et al*. (2012) and Aiyedun *et al.* (2011).

Research works by Adetunji *et al.* (2011, 2012) and Adetunji and Aiyedun (2012), investigated corrosion behaviour / resistance of Austenitic Stainless Steel and Aluminium Zinc Alloy coated steel in cassava fluid, maize pulp and seawater solution; while Adeleke *et al.* (2012a and 2012b), Adeleke *et al.* (2013), investigated the effects of Reflux Ratio on the Design of Distillation Column of a Bio-ethanol Plant using Cassava as Feedstock; A Parametric study of the effect of Relative Volatility of the Feed on the Design, and A New Simulation Model for Design of Distillation Column in a Bio-ethanol/Water System: the effect of Reflux Ratio.

3.5 Areas of Minor Research

Mr. Vice-Chancellor, Sir, distinguished ladies and gentlemen, in the course of this lecture, I have delivered highlight of my contribution to knowledge in the main area of focus of my research (hot rolling of stainless steel), the presentation has been brief because of limited space and time. However, there are other minor areas where I have made notable contribution to knowledge in the course of my journey to the professorial chair. Permit me to briefly touch these areas as well.

3.5.1 Integrated Steel Plants

1. Layout Requirements for Integrated Steel Plants

Earlier in 1975, I produced a general layout and transportation drawings for a 1.5 MT/year Integrated Steel Plant – (Biladilla Steel Plant) in India.

An integrated steel plant is characterized by its basic metallurgical processes, material flows and functions, which call for proper co-ordination of supply and facilities, disposition of shop areas and equipment, design of the material handling systems, etc. All these have considerable bearing on the efficient working of the steel plant. You will recall, earlier in this lecture, that I informed this gathering that I was fully involved in the Layout and Transportation calculations for Ajaokuta Steel Plant at that time with Tiajprom export of USSR.

I took a further step in highlighting the basic requirements for integrated steel plants and outlined the procedures for verifying these basic requirements. Looking at Aladja Steel Plant as a case-study and based on these basic procedures, it was pointed out that the productivity problems of Aladja Steel Plant were not related to its layout (Aiyedun, 1994).

3.5.2 Energy Studies

Some earlier work was done on experimental investigation of a partially insulated solar water heater with natural circulation (Afeti *et al.*, 1991a) and, some transport and thermodynamic properties of selected edible oils (Afeti *et al.*, 1991b).

Modest contribution was also made to the frontier of knowledge in Energy Studies through a joint research with Ologunye on Energy Efficiency in a Private Sector Production Company in 2001. In addition, a collaborative research was undertaken on Energy Efficiency of a Private Sector with 7Up Company, Nigerian Eagle Flour Mills Ltd, Ibadan, as case studies (Aiyedun and Ologunye, 2001; Aiyedun and Onakoya, 2002; Aiyedun *et al.*, 2008). A recent work on Development of Vehicle Emission Reduction Unit (VERU) for use in Petrol Engines was carried out by Ismaila *et al.*, (2012). This equipment absorbs certain percentages of CO_2, CO and HC which would have been emitted into the atmosphere.

3.5.2. Other minor areas of research

(i) Design of a Highway Side Retractable Shrub/ Grass Cutter

A retractable shrub/grass cutter mounted on a 53 kW power tractor and using it as its prime mover was designed to address the problem of bushy highway grass/shrubs. The cutter is capable of cutting grass and shrubs (of less than 40 mm diameter) to a height of 30mm above the road surface and a depth of 1 meter inward from the edge of the road. It uses the rotary motion for its flywheel at 3000 rpm, which is transferred into a reciprocating motion of the cutter knife. To avoid obstacles on its path, the cutter assembly was made retractable via a manually operated power screw and a combination of universal and knuckle joints. The design is functional, manually operated and economical. It can be adopted for mounting on other vehicles and can be adapted for the harvesting of wheat and kenaf (Aiyedun and Buggu, 2003).

(ii) Pyrolysis of Shredded Plastic Waste.

Last but not the least on other minor areas of research is on waste recycling. One of the methods of waste treatment and resource recovery is pyrolysis. In the work, 85 kg of shredded plastic waste was pyrolysed. The waste was divided into six different masses as feedstocks for the reactor and each feedstock was pyrolysed for between 6.5 and 8.0 hours. Between 0.2 and 0.5 dm^3 of tar oil was produced from the feedstock. Waste volume reduction was between 84.69 and 85.82%. The conclusion drawn showed that appreciable volume of tar oil can be produced per kg of plastic waste pyrolysed and as high as 85.25% average waste reduction can be achieved (Ojolo *et al.*, 2004).

4.0 CONCLUSIONS

Mr. Vice-Chancellor, Sir, Distinguished Scholars, Ladies and gentlemen, while showing immense appreciation for the precious time you all have sacrificed for this lecture, the conclusions and recommendations to be drawn are multifaceted.

Iron and steel is indeed the life-wire of industrial development. In fact, no one would deny that iron and steel is of tremendous importance in every day life, despite the fact that new chemical materials, such as, plastic, synthetic resins and metals like aluminium and others multiply at an increasing pace, the role of iron and steel does not diminish, rather it acquires new application in outer space, mining and drilling for mineral resources on the mainland and below the ocean floor, in nuclear power engineering, transportation, communication, electronics and agriculture (especially the food industry).

With less than $500 million required to complete the Ajaokuta Steel Complex (Adelakun, 2002), it is imperative to bring the project to completion. Considering the importance of the plant to Nigeria's industrial growth, the amount required to fully complete the facility, which is 90-95% technically worthy, is insignificant for an oil-producing nation like Nigeria. Full operation of the Ajaokuta Steel Complex, no doubt, is what Nigeria has been waiting for to achieve some form of industrial regeneration and technological take off.

There is no gain saying that if Ajaokuta Steel Complex sees the light of the day and Delta Steel Plant Aladja is revamped and they both play the part on which they were originally designed to play, they will catalyze industrial development in the country through numerous upstream and downstream industries that will use their products and Nigeria will surely come out of the group of underdeveloped nations to become a fast developing nation.

Mr. Vice-Chancellor, Sir, Distinguished Scholars, Ladies and gentlemen, on the new hot rolling model, the roll chilling effect accounted for in the reverse sandwich model has led to better agreement between the predictions of this Reverse Sandwich Model (RSM) and experimental results in the hot rolling of Type 316 stainless steel. Temperature distribution, rolling load and torque are now predicted with better accuracy than what was obtainable using Sims theory or the Bland and Ford's theory.

5.0. RECOMMENDATION

A. For the Nation

1. Government should enter into joint partnership with the foreign steel companies that constructed the Ajaokuta Steel Company, for its completion and operation, and run both Integrated Steel Plants in Ajaokuta and Aladja in a holistic manner.

2. Completion and Operation of the Warri-Ajaokuta rail line with needed rolling stock and its Operation and Maintenance Company put in place.
3. Dredging of Warri Port to 10-12m draft, provision of handling facility for Coals, Hot Briquette Iron (HBI), etc at DSC harbor and accommodation of 50,000-100,000tons ships on the harbor.
4. Special/Captive Electricity Generation Plants at DSC and Ajaokuta Steel Plant will meet their electricity demands and the remainder can be added to the National Grid.
5. Reduction and retraining of needed work force at both plants for economic viability.
6. Introduction of flat product lines into both plants to meet the local market demands and sales to the West African sub section.
7. Production of Hot Briquette Iron (HBI) for export at DSC and the installation of a Hot Strip Mills at ASCL and DSC to meet the flat steel products demand of the country.

B. For FUNAAB

1. The College of Engineering of this University cannot be fully established and developed without adequate funding for modern research/workshop facilities. Workshop equipment like CNC Machines, Scanning Electron Microscope (SEM), Nano-technology Research Equipment, etc are needed.
2. Our research focus in Engineering should be in the areas

of Agricultural products and inputs of Engineering into Agriculture as well as on the minerals, raw materials of our Geographical zone.

C. For College of Engineering

1. The College has come to stay in this University and the effects of our contributions are already being felt both nationally and internationally. We need to note that "No man having put his hands to the plow and looking back is fit for the Kingdom of God" (Luke 9: 62, KJV).
2. Let us catch a niche for ourselves by making our research focus relevant to specific national needs, the University focus on Agriculture and the local/raw materials of our geographical zone.

6.0 ACKNOWLEDGEMENTS

Firstly, I give thanks to the Almighty God for His abundant mercies and unfailing love for me and my loved ones. I am where I am today by His grace and I give Him all the glory.

I acknowledge the love and support of my late father, Pa Moses Aiyedun and my late mother, Mrs. Rebecca Aiyedun, they were my role model. When I wanted to give up schooling in primary school, it was my mother who encouraged me. In 1972, when I graduated with a Second Class Upper Division, my father called me and said "your brothers said that you were

invited for further studies but you turned it down. Do you know that in future Nigeria, second and third degrees may find it difficult to get jobs"? I worked for six years in the Industry before going for my MSc and Ph.D. By the time my father passed on to glory in 1982, I thank God that I was on my Ph.D research, but what he predicted started happening in Nigeria around 1980 and is still happening now. Though both of them are not here today to share this joy, this lecture is dedicated to them, and I am indeed very grateful for their love and sacrifice and for showing me the true and only WAY.

My senior brothers and sisters were great trail blazers for those of us coming behind. Mrs. Mary Oderinde, Elder J. K. Aiyedun (who brought me up as "Omo teacher" thank you.) Chief Mrs. A. F. Olatunde, Bro. John Aiyedun, Late Prof. B. A. Aiyedun, Dr. Joel Aiyedun and my junior brother, Dr. Kola Aiyedun. Thank you all for being there for me.

I remember with gratitude my late grandfather-in-law, Papa E.A. Lewis of Oke Ado, Ibadan, my late father and late mother-in-laws: Pa Akintunde Ajose-Adeogun and Mrs. B. Y. Ajose-Adeogun of Isale Eko, Lagos, thank you for the wonderful support I received from you all. I want to thank all my relations and in laws here present at this joyous occasion.

I thank my secondary, post-secondary school teachers who moulded my life in those formative years, especially, Mr. Finlayson, (Titcombe College, Egbe), Mr. A. W. E. Winlaw (FGC, Warri), Chief Olaniyan (FGC, Sokoto).

I want to express my sincere gratitude to my lecturers who have contributed in one way or another to my academic enrichment especially, the contributions of the following: Late Dr. L. G. M. Sparling (Mechanical Engineering Department), Emeritus Prof. C.M. Sellars (Metallurgy Department), both of University of Sheffield, U.K., for supervising my Ph.D research. They gave me a solid foundation in research.

The following were my bosses in the Industry and in Academics, they believed in me and they encouraged me to greater heights, I am indeed grateful: Late Prof. Adekola Snr. (appointed me as a Senior Lecturer in ATBU, Bauchi, on completion of my Ph.D); Prof. A. F. Oluwole, NNOM. (employed me as a Nuclear Engineer for OAU, and approved my being given scholarship for my MSc and DIC in Nuclear Engineering); Engr. Akin Adegboye and Engr. Prof. Steve Ojobor (employed me in Nigerian Steel Development Authority, Lagos and Delta Steel Plant, Aladja and gave me opportunities for various trainings and advancement). I thank my former V.C, Prof. I.F. Adu, for appointing me as a Professor of Production Engineering in 2005 and for also appointing me as the Dean (COLENG), 2005-2008.

I thank my Vice Chancellor, Prof. O.B. Oyewole, all past Deans of the College of Engineering, FUNAAB, Prof. Bayo Adegboyega, Late Prof. Olusegun Adebisi, Prof. E.S.A. Ajisegiri, and my current Dean, Prof. S.B. Adejuyigbe. Thank you for allowing me to present this 42nd Inaugural Lecture. Other *Egbons*, Professors, friends and colleagues who have been of great encouragement are Prof. J.O. Olayemi (ABU), Prof. A.A. Aderoba (FUTA), Prof. S.A.Adekola (UNILAG), Prof. J.O.Akingbala (U.I), Prof. Ayo Ogunkunle (UI), Late Prof. O.O. Akindele (UNILAG), Late Dr. J. S. Adeoti (UNILORIN); Dr. S.J. Ojolo, Dr. O.S. Adeosun (UNILAG), Dr. O.J. Alamu (UNIOSUN), Dr. G.M. Afeti, Dr. E.S.D. Afrifa (GHANA). Thank you all for being there for me.

Quoting from a quote by Olufayo (2009) "the most concern of a university researcher is not in obtaining money or grant to carry out research but in getting the right student".

I appreciate and say thank you to all my research students over the years, both at Masters and Ph.D. levels. Dr. O.S. Adeosun (Sub Dean PG School, UNILAG), Dr. O.J. Alamu (Director Academic Planning, UNIOSUN), Dr. O.S. Olokode (my present Ag. HOD), Dr. E.A. Adeleke (UNIOSUN), Dr. O.R. Adetunji, Engr. N.O. Adekunle, Engr. O.S. Igbudu, Engr. L.E. Osegbale, Engr. B. Shobowale, and all others too numerous to mention.

My twelve years in Mechanical Engineering Department, University of Ibadan, was very rewarding. I appreciate the contributions of all staff of the Department to my academic life, especially, Prof. A.O. Bamiro, Prof. O. Ofi, Prof. R. O. Fagbenle and Prof. B. Alabi, and all other academic, technical and administrative staff of the Department.

All staff of my present Department under the able leadership of the Acting Head of Department, Dr. O.S. Olokode are all gratefully acknowledged.

I also want to appreciate some individuals and families who have contributed to my life spiritually and otherwise: Rt. Rev. and Mrs. J.A.F Olusola (Lord Bishop of Ipetu-Ijesha Anglican Communion), Pastor and Mrs. Blessed K. Musa (Jos), Ven. Dr. Adams Onuka (U. I). Pastor and Mrs K. Akingbade (Ibadan), Rev. E.A. Ayoola (Ibadan), Pastor Oyelola (Baba Ogbomoso), Very Rev. T. Olatunji, and the Chaplaincy (Chapel of Resurrection, U. I), Pastor and Mrs. I. Osho (Ibadan), Rev. and Mrs. I. Omolehin (Ilorin). All members of U.I. Christian Family Fellowship, U.I. Chapel of Resurrection Bible Study Teachers, Men's League (U.I Chapel of Resurrection) and all other ministers of God who have been Co-labourers with us in His Vineyard, thank you. By His Grace, we shall not loose our rewards, Amen.

I thank Sir and Lady A.U. Oboite and Pa Engr. E. O. Oluwole and Late Mrs. L. A. Oluwole for being there for me as fathers and mothers in Ibadan.

I am also indebted to various organizations and awarding bodies for scholarships/fellowships/trainings received during the course of my career:

- Kwara State Government (Scholarship for B. Eng.)
- Obafemi Awolowo University (Scholarship for MSc)
- Federal Government of Nigeria (Scholarship for Ph.D)
- Nigerian Steel Development Authority (Steel Plant training fellowship)
- O.A.U, Ile-Ife (Nuclear Tandem Accelerator training fellowship)
- D.S.C, Aladja (Pellet and Lime Plant and General Management training fellowship)
- University of Lagos (Sabbatical Leave and study leave)
- University of Ibadan (Sabbatical Leave)

May I also appreciate my wonderful friends, particularly, Mr. J.A. Amusan, Mr. Layi Adeboye, Mr. Hakeem Ajose-Adeogun (Former Provost, Adeniran Ogunsanya College of Education, Ijanikin, Lagos), Mr. Taiye Fadairo (College of Education, Oro, Kwara State), all members of Club K25 of Kwara State, and all those who have contributed to this lecture directly or indirectly: Special thanks to Engr. Benedict Anyanwu, Mrs. R.O. Ogunsola (Mechanical Engineering Department, FUNAAB).

Finally, I thank the All-knowing God, for giving me my soulmate over the past thirty three years since we got married; Mrs. Adedayo Olakunbi Aiyedun (Nee Ajose-Adeogun). She has been a lady of honour, faith and patience, a virtuous woman, very understanding and accommodating, prayerful, a darling wife and most especially my best friend. Thank you for your unfailing love, support and understanding.

I also thank our three wonderful children and two grandchildren, Mrs. Toluwalase Oyebode (Nee Aiyedun), and her husband Dr. Dele Oyebode; Dr. Temitope Aiyedun and Mr. Oloruntoba Aiyedun (Ex. Funaabite), Oluwafeyitamilore Oyebode and Oluwarantimisirere Oyebode. They have, indeed, been and will continue to be God's special blessings to us and to their generation.

It has been a long journey since graduating in 1972, from industry to academics to industry back to academics, to the industry and finally back in academics. I give all the glory, honour and majesty to the KING of Kings and LORD of Lords, the Lord Jesus Christ for the unsearchable riches of His grace and faithfulness over the years.

Mr. Vice-Chancellor Sir, distinguished ladies and gentlemen, I thank you all for listening and God bless. *Adelebare, Arin na kore!*

7.0 REFERENCES

Adelakun, S.A. 2002. “Viable options for the development of the Nigerian Metallurgical Industry”. A key note paper: *Proceedings of Nigerian Materials Congress, NIMACON* 2002, EMDI, Akure, Nigeria, Nov. 11-13, 2002.

Adeleke, A.E., **Aiyedun, P.O.,** Waheed, M.A., Sanni, L.O., Olawale, S.O.A., Dairo, O.U. 2013. “A New Simulation Model for Design of Distillation Column in a Bio-ethanol/Water System: Effect of Reflux Ratio”. *British Journal of Applied Science and Technology* 3(3): 508-517, 2013.

Adeleke, A.E., Alamu, O.J., Olawale, O.A., **Aiyedun, P.O.,** Dairo, O.U. 2012 “A Parametric Study of the Effect of Relative Volatility of the Feed on the Design of Distillation Column of a Bioethanol Plant Distillation Column of a Bioethanol Plant using Cassava as Feedstock”. *Transnational Journal of Science and Technology,* Vol.2, No. 11, pp.74-88, December 2012.

Adeleke, A.E., **Aiyedun, P.O.,** Waheed, M.A., Sanni, L.O., Olawale, S.O.A., Dairo, O.U. 2012 "Effect of Reflux Ratio on the Design of Distillation Column of a Bioethanol Plant using Cassava as Feedstock". *Energy Technology and Management Conference (ETM Con 2012)* U.I. Ibadan. pp.62-75

Adetunji, O.R., **Aiyedun P.O.** 2012. "Corrosion Behavior of Aluminium Zinc Alloy Coated Steel in Cassava Juice, Maize Pulp and Sea water Solution". *The Pacific Journal of Science and Technology, Volume 13.* Number 2, pp.13-17 (Fall). http://www.akamaiuniversity.us/PJST.htm

Adetunji, O.R., **Aiyedun P.O.,** Arowolo, T.A., Alamu, O.J. 2012. "Corrosion Resistance of Austenitic Stainless Steel in Cassava Fluid, Maize Pulp and Seawater". *The Pacific Journal of Science and Technology, Volume 13.* Number 2, pp.8-12 (Fall). http://www.akamaiuniversity.us/PJST.htm

Adetunji, O.R; **Aiyedun**, **P.O;** Alamu, O.J and Surakat, A.S. (2011) "Electrochemical properties of metals in cassava fluid". *Journal of Engineering and Technology Research.* Vol. 3(10) pp. 292-297.

Afeti, G.M., Ezeji C.O., **Aiyedun, P.O.** 1991. "Some Transport and Thermodynamic properties of selected Edible Oils". *AMSE Transactions, AMSE Press,* Vol. 8. No 2, pp39-48.

Afeti, G.M., Imide, N.E., **Aiyedun, P.O.** 1991. "Experimental Investigation of a Partially Insulated Solar Water Heater with

Natural Circulation". *Energy Conversion Management,* Vol. 32, No. 2, pp. 145-151, 1991.

Afonja, A. 2002. The Materials World: *A Keynote Paper, Proceedings of the Nigerian Materials Congress (NIMACON 2002)*, Engineering Materials Development Institute, Akure, Nigeria, Nov. 11-13, 2002.

Afonja, A.A., Sansome, D.H. 1973. "A Theoretical Analysis of the Sandwich Rolling Process". *Int. J. Mech. Sci.,* 15 (1): 1 – 14.

Aiyedun, P.O. 2006a. "Influence of Composition on Strength and Microstructure of Hot Rolled HC SS316 and LC SS316". *Nigerian Journal of Science (NJS), Science Association of Nigeria.* Vol.40 (2006): p.1-11.

Aiyedun, P.O. 2006b "Microstructural changes During and After Hot Rolling of HCSS316". *Proceedings of Material Society of Nigeria (MSN) Annual Conference, NIMACON 2006,* Abuja, Nigeria. 13th -17th Nov. 2006. pp.58-61.

Aiyedun, P.O 2005. "Layout Requirements for Integrated Steel Plants". *Engineering and Technology research Journal, Faculty of Engineering, Technology & Environmental Sciences,* LASU, Epe Campus, Lagos State. Vol. 1, No. 2, 2004, pp. 71-82.

Aiyedun, P.O. 2004. "Comparison of Load and Torque obtained by three different Rolling Theories for HCSS316 Hot flat rolled at low reduction and low strain rates". *MANUTECH-2004 Conference Proceedings for 7th Africa-USA International Conference on Manufacturing Technology:* Theme: Connecting Africa to Global Manufacturing: Opportunities and Challenges. July 12 – 14, Hotel Presidential, Port Harcourt, Nigeria. pp. 374-386.

Aiyedun, P.O. 2002. "Spread Calculation for Steel (HC SS316) Hot Flat Rolled at Low Strain Rates". *NIMACON-2002: Nigerian Materials Congress Proceedings, Nov. 11-13, 2002 EMDI,* Akure, Theme: Engineering Materials and National Development, pp. 287-292.

Aiyedun, P.O. 1999. "Yield Stress Variation across Thickness for Steel (HC SS316) Specimen Hot Rolled at Low Reduction and Low Strain Rates". *NSE Technical Transactions,* Jan. – Mar., Vol. 34, No. 1, pp. 46-70.

Aiyedun, P.O. 1997. "Microhardness Across Thickness for Stainless Steel (SS316) Hot Rolled at Low Strain Rates and Reductions". *Journal of Engineering Research,* Vol. JER-55, Aug. 1997, No. 2, pp. 29-43.

Aiyedun, P.O. 1994. "Layout of Integrated Steel Plants-Environmental Engineering Aspects". *NSE Technical Transactions:* Vol. 29, No. 4, pp. 58-80; Oct. – Dec., 1994.

Aiyedun, P.O. 1986. "Hot Flat Rolling Simulation by Use of the Bland and Ford's Cold Rolling Theory for HCSS316 at Low Reduction and Low Strain Rates". *Proceedings Int. AMSE Conference on Modelling and Simulation, Williamsburg, Virginia, USA,* Sept., 3-5, 1986, Vol. 3, pp. 14-36.

Aiyedun, P.O. 1984. "A Study of Loads and Torques for Light Reduction in Hot Flat Rolling". *Ph. D. Thesis, University of Sheffield.*

Aiyedun, P.O. 1976. DPR – "General Layout and Transport of a 1.5 MT/year Integrated Steel Plant – (Biladilla Steel Plant)". *MECON, Ranchi India,* pp. 1-23.

Aiyedun, **P.O.,** Igbudu, O.S., Bolaji, B.O. 2011 "Simulation of Torque during Rod Rolling of HC SS316 at low strain rate using 'Phantom Roll' Method". *Journal of Minerals & Materials Characterization & Engineering.* Vol. 10, No. 15, pp. 1473-1485, 2011 jmmce.org

AIYEDUN, P.O., Olokode, O.S., Oyeleke, Y.T., Lee, W.E., Anyanwu, B.U. 2011. "Studies on the Five (5) Selected Clays in Abeokuta, Nigeria". *Nigerian Materials Congress 2011*

(NIMACON 2011), Nov. 21-24, 2011, EMDI, Akure, Nigeria. pp.429-434.

Aiyedun, **P.O.,** Oseghale, L.E., Alamu, O.J. 2009. "Simulation of load bearing rod rolling of carbon-manganese steel using the phantom roll method". *Pacific Journal of Science and Technology.* http://wwwakamaiuniversity.us/PJST.htm. Vol.10, No 1, May 2009 (spring). Pp.4-14.

Aiyedun, P.O., Aliu, S.A. 2009. "Rolling temperature for steel hot flat rolled at low strain rates". *Advanced Materials Research:* Vols.62-64 (2009). Pp. 317-323.

Aiyedun, P.O., Adeyemi, O.A., Bolaji, B.O. 2008. "Energy Efficiency of a Private Sector with Nigerian Eagle Flour Mills Ltd, Ibadan as a case study". *ASSET Journal, Series B,* Vol.17, No.1.

Aiyedun, P.O., Igbudu, S.O., Bolaji, B.O. 2008. "Simulation of load during rod rolling of HCSS316 at low strain rates". *Proceedings 2nd International conference on Engineering Research and Development Innovation (ICER&D) 2008, University of Benin,* 14-17 April, 2006, Paper No. ICERD08084; pp. 422-430

Aiyedun, P.O., Buggu, L.T. 2003. "Design of a Highway Side Retractable Shrub/Grass Cutter". *Nigerian Journal of Engineering*

Research and Development Vol. 2, No. 2, April-June, 2003, pp. 50-59.

Aiyedun, P.O., Shobowale, B. 2003. "Development of a Reverse Sandwich Model (RSM) for Calculating Rolling Load and Torque for Steel (HC SS316)". *NIMACON-2003: Nigerian Materials Congress Proceedings.* Nov. 12-14, 2003 EMDI, Akure, Theme: Materials Development. Pivotal to National Industrialisation pp. 124-131.

Aiyedun, P.O., Lawal, J.B. 2002. "Yield Strength Estimation for Stainless Steel using Torsional Test". *Nigerian Journal of Engineering Management (MJEM),* Vol. 3, No. 1, 2002, pp. 69-79.

Aiyedun, P.O., Onakoya, B.A. 2002. "Energy Efficiency in a Private Sector Production Company". *Nigerian Journal of Industrial and Systems Studies,* Vol. 1, No. 4, 2002, pp. 15-24.

Aiyedun, P.O., Ologunye, O.B. 2001. "Energy Efficiency of a Private Sector with Cadbury Nigeria Plc., Ikeja, Lagos as a Case Study". *NSE Technical Transactions,* Vol. 36, 2001, No. 2, pp. 59-66.

Aiyedun, P.O., Sellars, C.M. 1998. "Effects of Fine Precipitate on the Strength of High Carbon SS316 Hot Flat Rolled at Low Reductions and Low Strain Rates". *NSE Technical Trans-*

actions 33 (4): 67 – 100.

Aiyedun, P.O., Sparling, L.G.M., Sellars, C.M. 1997. "Temperature Changes in Hot Flat Rolling of Steels at Low Strain Rates and Low Reduction". *Pro. Instn. Mech. Engrs.* Vol 211, Part B, pp. 261-254.

Alamu, O.J., **Aiyedun, P.O.,** Adekunle, N.O. 2009. "Effect of pass reduction on rolling parameters using reverse sandwich model integrated into the hot rolling Bland and Ford's theory". *Advanced Materials Research.* Vols.62-64 (2009). Pp. 385-392.

Alamu, O.J., **Aiyedun, P.O.,** Kareem, A., Waheed, M.A. 2007. "Effect of AISI 316 stainless steel Geometry on Temperature Distribution during Hot Rolling at High Reduction". *Advanced Materials Research Edited by Akii Ibhadode, Published by Trans Tech Publications Ltd.,* Switzerland Vol. 18-19, PP 195-200

Alamu, O.J., **Aiyedun, P.O.** 2003. "The Influence of Ingot Geometry on Temperature Distribution in HC SS316 during Hot Rolling". *Lautech Journal of Engineering and Technology,* Vol. 1, No. 1, 2003, pp. 47-63.

DSC Orientation Course Part 2, (1980): *Prepared by Voest-Alpine Ag. CSA Nigeria.* Pp.124 & 143.

eHow.com 2013 "Commercial Uses for 303, 304 or 316 Stainless Steels". http://www.ehow.com/info-8250073-commercial-304-316-stainless by *Les Moore, eHow Contributor.*

El-Kalay, A. K. E. H. A., Sparling, L.G.M. 1968. "Factors affecting Friction and their Effect upon Load, Torque and Spread in Hot Flat Rolling". *Journal of the Iron and Steel Institute,* vol.206, pp.152-163.

Ismaila, S.O., Odetokun, B.D., Bolaji, B.O., Waheed, M.A., **Aiyedun, P.O.** 2012. "Development of Vehicle Emission Reduction Unit (VERU) for use in Petrol Engines". *SIGURNOST* 54 (3) 285-292 (2012), Publication of the Institute of Safety Research & Development, Zagreb.

ISSF, 2010 "Stainless Steel in the Dairy Industry; A Sustainable Solution for Human Diet". *ISSF 2010. International Stainless Steel Forum.* Rue Colonel Bourg. 120, 1140 Brussels, Belgium. www.worldstainless.org

Olufayo, A.A. 2009. "Water Management at Farm Level: more crop per drop". *Inaugural Lecture,* No.52, FUTA, Akure.

Olokode, O.S., **Aiyedun, P.O.,** Raheem, D.M., Owoeye F.T., Anyanwu, B.U. 2012. "Production and Characterization of Clay-Cow Dung Insulating Fire Bricks". *Global Advanced Re-*

search Journal of Engineering, Technology and Innovation (ISSN: 2315-5124) Vol. 1 (7), pp 162-167, October, 2012.

Olokode, O.S and **AIYEDUN, P.O.** 2011. "Mineralogical Characteristics of Natural Kaolins from Abeokuta, South-West Nigeria". *The Pacific Journal of Science and Technology (PJST).* Vol. 12, No. 2, pp. 558-565.

Ojolo, S.J; Bamgboye, A.I; **Aiyedun, P.O.,** Ogunyemi, A.P. 2004. "Pyrolysis of Shredded Plastic Waste". *MANUTECH-2004 Conference Proceedings for 7th Africa-USA International Conference on Manufacturing Technology:* Theme: Connecting Africa to Global Manufacturing: Opportunities and Challenges. July 12 – 14, Hotel Presidential, Port Harcourt, Nigeria. pp. 480-486.

Prasad, M.S., Reid, K.J., Murray, H.H. 1991. "Kaolin: processing, properties and applications". *Applied Clay Science,* 6 (1991) 87-119, Elsevier Science Publishers B.V., Amsterdam.

Ronald, H. Schmidt and Daniel J. Erickson. 2011. "Sanitary Design and Construction of Food Equipment". *FSHN0409/FS119, University of Florida,* IFAS Extension.

Rex, M. 2002. "Environmental aspects of the use of iron and steel slags as agricultural lime". *Proceedings of the 3rd European*

Slag Conference, Keyworth, Nottingham, U.K. Oct., 2002.

Schaffer, P.J., Sexana A., Antolovich, D.S., Sanders, T.H., Warner B.S. 1999. "Science and Design of Engineering Materials". *2nd edition, McGraw-Hill Company Inc.*, pp. 679-680.

Sellars, C.M. 1995. "Metallurgical Modeling of Thermomechanical Processing". *50th Hatfield Memorial Lecture, IMMPETUS,* University of Sheffield, Sheffield, U.K.

Sellars, C.M. 1984. "Computer Modelling of hot working processes." In "Perspective in Metallurgical Developments". *Centenary Conference Proceedings;* Dept. of Metallurgy, University of Sheffield, U.K. pp. 209-227.

Sellars, C.M. 1981. "Les Traitments Thermomeeaniques". *24eme Colloque de Metallurgie, Institut National des Sciences et Technique Nucleaires,* Sanclay, France. Pp. 111-120.

Sellars, C.M., Sah, J.P., Baynon, J.H., Foster, S.R. 1976. "Plane Strain Compression Testing at Elevated Temperatures". *Report on Research Work supported by SRC Grant No. B/R6/1481,* University of Sheffield, U.K.

Serajzadeh, S., Taheri, A.K., Mucciardi, F. 2002. "Prediction of Temperature Distribution in the Hot Rolling of Slabs". *Model-*

ling Simul. Mater. Sci. Eng. Vol.10, pp. 185-203.

Teresa A. Branca and Valentina Colla 2012. "Possible Uses of Steel making slag in Agriculture: An Overview". *Material Recycling Trends and Perspectives. Ed. Dr. Dimitris Achilias.* ISBN 978-953-51-0327-1 pp. 335-356.