THE EFFECTS OF WELDING AND HEAT TREATMENT ON MECHANICAL PROPERTIES OF DUPLEX STAINLESS STEELS.

BY

TANIMU IBRAHIM
MSC/ENG/9621/2009-2010

A Thesis Submitted to the School of Postgraduate Studies Ahmadu Bello University, Zaria

In partial fulfillment of the requirements for the Award of Masters Degree in Mechanical Engineering

Department of Mechanical Engineering, Faculty of Engineering
Ahmadu Bello University, Zaria,
Nigeria.

1st FEBRUARY, 2013.

DECLARATION

I hereby declare the work in this thesis titled **''THE EFFECTS OF WELDING AND HEAT TREATMENT ON MECHANICAL PROPERTIES OF DUPLEX STAINLESS STEELS''** was performed by me in the Department of Mechanical Engineering under the supervision of Prof. S.Y.Aku and Dr. D.S.Yawas.

The information derived from the literature has been dully acknowledged in the text and a list of references provided. No part of this work has been presented for another degree or diploma in any institution.

Tanimu Ibrahim

_____	_____	_____
Name	**Signature**	**Date**

CERTIFICATION

This thesis titled **''THE EFFECTS OF WELDING AND HEAT TREATMENT ON MECHANICAL PROPERTIES OF DUPLEX STAINLESS STEELS''** meets the regulations governing the award of degree of master of science of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

Prof. S.Y.Aku

_____	_____	_____
Chairman, Supervisory committee	**Signature**	**date**

Dr. D.S.Yawas

_____	_____	_____
member, Supervisory committee	**Signature**	**date**

Dr. M.Dauda

_____	_____	_____
Head of Department	**Signature**	**date**

Prof. A.A Joshua

_____	_____	_____
Dean School of Post Graduate Studies	**Signature**	**date**

DEDICATION

This thesis is dedicated to Almighty God, in whom I found grace to complete this work and to my late parent Mr Ibrahim.S.Kogi and Mrs Mary Kogi.

ACKNOWLEDGMENT

First of all, I wish to thank my academic supervisors Professor S.Y.Aku and Dr.D.S.Yawas for their assistance, guidance valuable academic discussions throughout this thesis, and without them this thesis would not have been possible. I also wish to sincerely appreciate all the members of my family for their support and encouragement. To my friends, a big thank you to you for always being there to encourage and advise me.

ABSTRACT

The effects of welding and heat treatment on mechanical properties of duplex stainless steel were investigated. The duplex stainless steel rod of 8mm diameter was cut into length of 100.2mm; they were further cut into two equal parts with the two faces beveled to have a 60° grooved angle, leaving a root and face gap of 2mm. The rods were then joined together using GMAW and SMAW processes using stainless steel coated electrode and bare wire electrode (E308L-16 and Nertalic 50). After welding, some specimens passed through stress relief and quenching heat treatment (in neem oil and gear oil (85W90)) and some samples served as standards for comparison and analysis. Tensile, Charpy impact and hardness tests were carried out. The results of the studies show that welding and heat treatment really affect the mechanical properties of the alloy, the control strength was 811.47MN/m^2 while that of gas metal arc welding (GMAW) it ranged from 177.07 to 257.32MN/m^2 and for shield metal arc welding (SMAW) from 452.23 to 678.98MN/m^2. The control impact energy was 162.70J, while that of the gas metal arc welding (GMAW) ranged from 38.64J to 56.20J and for shield metal arc welding (SMAW) ranged from 148.70 to 156.02J. It was also noted that shield metal arc welding (SMAW) gives better results close to the as received than the gas metal arc welding (GMAW) process and heat treatment improved the mechanical properties of the alloy after welding. The research also showed that the stress relief heat treatment gives better strength (A_3 =331MN/m^2 and B_3 =665MN/m^2) compared to those that were quenched in lubricating oil (A_2 =329MN/m^2 and B_2 =601MN/m^2) and neem oil (A1 =222MN/m^2 and B_1 =566MN/m^2), while those that were quenched in lubricating oil and neem oil had higher toughness.

TABLE OF CONTENTS

Declaration……..i

Certification…….....ii

Dedication……..iii

Acknowledgment…….....iv

Abstract…….....v

Table of Contents…….....vi

List of Figures…….....ix

List of Tables…….....x

Plates of Micrographs……..x

Appendices …….....xi

CHAPTER ONE

INTRODUCTION

1.1 Overview…….....1

1.2 Statement of the Problem …….....2

1.3 Present Work.....4

1.4 Aims and Objectives…….....…4

1.5 Scope of the Study …….....5

1.6 Significance of Research.....6

CHAPTER TWO

LITERATURE REVIEW

2.1 Stainless Steels …….....8

2.2 Welding Process and its Characteristics…….…….....23

2.3 Welding Consideration for Duplex Stainless Steel …….……...27

2.5 Review of Past Work…… …….…….....31

CHAPTER THREE

MATERIAL AND METHODS

3.1 Materials and Equipment…… …….....34

3.2 Methodology…… …….....35

3.2.1 Pre-welding Sample Preparation……..35

3.2.2 Welding Procedure……..…….....36

3.2.3 Post Welding Thermal Treatment…….....37

3.2.4 Mechanical Test Procedure…….…….....38

3.2.5 Microstructural Analysis…….…….....41

3.3 Sample Labeling …….....42

CHAPTER FOUR

RESULTS AND DISCUSIONS

4.1 Results …….....43

4.2 Discussions …….....60

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions.....63

5.2 Recommendations.....63

References.....64

LIST OF FIGURES

Fig 2.1 Principal cross-section of a corrosion pit.....22

Fig 2.2 Iron cementite phase diagram (www.asminternational.org).....34

Fig 3.1 Joint preparation for V-groove welding.....42

Fig3.2 Welded Sample.....43

Fig 3.3 Gemco Furnace…….....44

Fig 3.4 Standard Sample for Tensile Test.....45

Fig 3.5 Standard Sample for Charpy Impact Test.....46

Fig. 4.1: Load vs Extension for Group B as Compared to Control.....61

Fig. 4.2: Load vs Extension for Group A as Compared to Control.....61

Fig. 4.3: Tensile Strength for Group A and Group B as Compared to Control C.....62

Fig. 4.6: Impact Energy for Group A as Compared to Control.....63

Fig. 4.7: Impact Energy for Group B as Compared to Control.....63

Fig. 4.8: Hardness Number for FZ of Group A as Compared to Control.....65

Fig. 4.9: Hardness Number for Group FZ of Group B as Compared to Control.....65

Fig. 4.10: Hardness Number for FZ and HAZ as Compared to Control.....66

LIST OF TABLES

Table 2.1: Physical Properties of Some Stainless Steels ……..…….....14

Table 2.2: Fe-C Phase Characteristics…….....33

Table 3.1 Sample Labeling.....49

Table 4.1: Research Material Chemical Composition.....50

Table 4.2: The Tensile Tests Results for Samples.....60

Table 4.3: The Impact Tests Results for Samples.....62

Table 4.4: Hardness Number for the Samples.....64

PLATES OF MICROGRAPHS

Plate 4.1: Micrograph of the Fusion Zone for Sample A.....51

Plate 4.2: Micrograph of the Heat Affected Zone for Sample A.....51

Plate 4.3: Micrograph of the Fusion Zone for Sample A1.....52

Plate 4.4: Micrograph of the Heat Affected Zone for Sample A1.....52

Plate 4.5: Micrograph of the Fusion Zone for Sample A2.....53

Plate 4.6: Micrograph of the Heat Affected Zone for Sample A2.....53

Plate 4.7: Micrograph of the Fusion Zone for Sample A3.....54

Plate 4.8: Micrograph of the Heat Affected Zone for Sample A3.....54

Plate 4.9: Micrograph of the Fusion Zone for Sample B.....55

Plate 4.10: Micrograph of the Heat Affected Zone for Sample B.....55

Plate 4.11: Micrograph of the Fusion Zone for Sample B1.....56

Plate 4.12: Micrograph of the Heat Affected Zone for Sample B1.....56

Plate 4.13: Micrograph of the Fusion Zone for Sample B2.....57

Plate 4.14: Micrograph of the Heat Affected Zone for Sample B2.....57

Plate 4.15: Micrograph of the Fusion Zone for Sample B3.....58

Plate 4.16: Micrograph of the Heat Affected Zone for Sample B3.....58

Plate 4.17: Micrograph for Sample C.....59

APPENDICES

Appendix A

Table A1: The Tensile Test Results for Sample A.....79

Table A2: The Tensile Test Results for Sample A1.....80

Table A3: The Tensile Test Results for Sample A2.....81

Table A4: The Tensile Test Results for Sample A3.....82

Table A5: The Tensile Test Results for Sample B.....83

Table A6: The Tensile Test Results for Sample B1.....84

Table A7: The Tensile Test Results for Sample B2.....85

Table A8: The Tensile Test Results for Sample B3.....86

Table A9: The Tensile Test Results for Sample C.....87

CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

Duplex stainless steels were first produced by Avesta Jernverk in the year 1929 with an alloy called 453E (25%Cr-5%Ni). Another record of the earliest production of duplex stainless steel products dates back to 1933 through an alloying error at J. Holtzer Company, France. An 18%Cr-9%Ni-2.5%Mo austenitic stainless steel grade was made to a 20%Cr-8%Ni-2.5%Mo composition containing a high volume of ferrite in an austenitic matrix. This two-phase material was then studied and it was found that when it was properly solution heat treated, the alloy was not sensitive to intergranular corrosion (IGC) in various corrosive environments; a significant advantage compared to fully austenitic stainless steel [Gunn, 1997].

However the development of duplex alloys suffered from many problems such as corrosion, ductility and welding. The real rapid development occurred in the 1970s with improved chemistry analysis capability and the introduction of the argon-oxygen-decarburization (AOD) refining process. The control of alloy chemistry and the removal of oxygen and sulfur were significantly improved in the early 1970s; the 22%Cr commercial grade duplex was developed in Germany and Sweden. It was claimed that this grade of duplex was not sensitive to IGC upon welding due to balanced chemistry [Charles, 1991].

In the 1980s, higher alloyed duplex stainless steel (DSS) grades were produced, and developed into super DSS. They were made to withstand more aggressive environments, but also bearing higher risk of precipitation due to the higher alloying element content. In the making of super DSS, Cr and Ni forming elements are balanced and more nitrogen is added.

From a welding point of view, the first duplex stainless steels available had poor weldability mainly due to lack of understanding of the metallurgical process that takes place in

the heat affected zone (HAZ). This brought about the second generation with improved weldability, mainly due to higher addition of nitrogen, and was developed in the early 80's; this was a significant breakthrough for these alloys (Claes-Ove, et al, 1995).The early duplex stainless steels did not also have an optimized ratio between ferrite and austenite. In most cases the ferrite content was too high (≈70%) causing the heat affected zones to be fully ferritic. These ferritic zones had inferior mechanical and corrosion properties and it is fully understandable why these steel grades were not popular in the beginning. The modern alloyed grades have an optimized ferritic (≈50%) and austenitic (≈50%) ratio in order to get a good austenite reformation in the heat affected zones and thereby good mechanical and corrosion properties of the welded joint. In addition the ferrites in the alloy also give rise to a lower coefficient of expansion than that of the austenitic steels, an advantage giving less distortion in the welded construction.

Furthermore the two phase structure of ferrite and austenite combines the beneficial effects of the phases and allowed the steels to obtain higher strength (due to ferrite) and toughness (due to austenite) even at low temperature (≈10^{o}C). The strength makes it possible to use thinner dimensions and accomplish weight savings. Other advantages of these alloys are satisfactory fatigue properties, modest thermal expansion and modest cost due to low nickel content.

1.2 STATEMENT OF THE PROBLEM

Reliability of an engineering structure requires that the quality or fitness for service aspect should be adequately addressed at various stages of design and fabrication. Despite incorporation of concepts of quality or fitness for service, engineering components are known to fail prematurely. And these failures can be described as a loss of function of a system or component due to some deficiency that limits their service life. Failures are common in most of

our industries and can take place at any of the various stages such as fabrication, testing, transportation and service (Bhaduri et al, 2003)

A large number of failures in industries are either directly or indirectly attributed to welds because of the inhomogeneity within the weldment, stress concentration, residual stress, inclusions etc. which invariably make it the weakest region. However a vast majority of repairs of failed components in industries are carried out using one of the welding processes and the success depends on many factors such as weldability of the material, type of damage, availability of suitable welding technique, possibility of carrying out pre-heating or post weld heat treatment, post repair inspection by non-destructive testing (NDT) techniques (Bhaduri et al, 2003).

Duplex stainless steels are increasingly used as structural materials in building and architecture because of their exceptional mechanical properties. Their room temperature yield strength in the solution annealed condition is more than twice that of standard austenitic stainless steels not alloyed with nitrogen. Over the last few years, they have started playing an increasingly important role in the construction of bridges, wherever specific environmental conditions combine with the need for high load-bearing capability. Duplex stainless steels are mostly selected because of their combination of high strength and corrosion resistance. Their full potential is used in locations where the material comes into contact with salt water, or where high concentrations of chlorides are present in the ambient air or where de-icing salts are of concern.

But with all their afore-mentioned favorable properties, they still fail mostly at the weld points which can be as a result of the welding process, process variables used and the welding environmental contamination. Hence, this research work is to verify the effect of welding process and heat treatment on the mechanical properties of welded duplex stainless steels. The mechanical properties under investigation are; tensile strength, impact strength and hardness**,** as

we already know that the durability of a welded structure directly depends on the resulting mechanical properties after welding. This work will also look at the effect of stress relief, and hardening (quenching and tempering) heat treatment on the mechanical properties resulting from welding of this alloy.

1.3 PRESENT WORK

This present work focuses on the effects of shielded metal arc, gas metal arc welding and heat treatment techniques on the mechanical properties of duplex stainless steel. The heat treatments to be carried out are stress relief, quenching in lubricating oil and neem oil and then tempering.

1.4 AIMS AND OBJECTIVES

The aim of this research work is to study the effects of welding and heat treatment processes on the mechanical properties of duplex stainless steels.

The specific objectives are;

i. To study the effect of welding methods on the stainless steel.

ii. To study the influence of different heat treatments on DSS mechanical properties after welding.

iii. To evaluate the effect of using different quenchants on mechanical properties of this alloy.

1.5 SCOPE OF STUDIES

This research covered the following areas:

i. The use of gas metal arc and shield metal arc welding process in the welding operation.

ii. The use of a heat treatment furnace for stress relieve, quenching and tempering post weld heat treatment.

iii. The use of grinding, polishing and lath machines to grind, polish and turn the samples before and after welding.

iv. The use of mechanical testing machine for tensile and impact test to establish the respective mechanical properties of the samples.

v. The use of a scanning electron microscope (SEM) to study the metallurgical microstructure of the samples.

vi. The use of hardness testing machine to check the local hardness of the samples.

1.6 SIGNIFICANCE OF RESEARCH

Due to recent evolution of raw material costs in production of stainless steels, particularly nickel, which has a drastic impact on austenitic grades surcharges; which are nowadays higher than the base materials price, several thousand Euros per ton are observed to be the price of the 300 series in last few years. Of course ferritic grades are almost not affected by these effects, but the replacement of the 300 series with the ferritic grade is not the answer where good mechanical and corrosion resistant properties are needed. (www.arcelormittal.com 18th Oct. 2011)

Duplex stainless steels started to be the cost competitive answer to both good mechanical properties and corrosion resistance compared to pure austenitic and pure ferritic (the constituent of the duplex grades). These lead to the replacement of 316 grade by 2205 duplex grade which are now considered to be cheaper grades, better corrosion resistant properties and high mechanical properties. The same trends are observed for 2304 duplex versus 304 grade, and super duplex versus 904L.

On the other hand, there have been reservations against full utilization of duplex stainless steels based on the lack of knowledge and standard codes for design because a fairly limited

amount of evaluation work has been conducted on DSS. Most of the studies were on austenitic stainless. As a result of these, engineers and material scientists are focusing their attention on how to improve the integrity of these important alloys in the open market, because lack of confidence in a material can lead to overly conservative decisions such as avoidance or over-specification particularly in high risk applications such as pressure vessels for which duplex grades should be the material of choice. New applications for duplex grades are arising daily as new grades with modified compositions are developed, requiring great knowledge of heat treatment, welding and alloying. Better knowledge of the mechanical properties of these alloys at welding is therefore necessary. This thesis takes up this problem for clarification where further knowledge has been deemed necessary. The information obtained will be used to enhance the usage of this grade of stainless steel in oil and gas industries, pulp and paper industries, and construction industries.

CHAPTER TWO

LITERATURE REVIEW

2.1 STAINLESS STEELS

In 1913 stainless steels were accidentally discovered by an English metallurgist named Harry Brearly, while working to improve rifle barrels. He discovered that by addition of chromium to low carbon steels it gave it corrosion resistance. (www.about.com, 18 October 2011).

Stainless steels are generally defined as an iron alloy containing a minimum of 10.5%wt of chromium. The properties of stainless steels are primarily determined by the presence of this chromium. Apart from carbon and chromium, modern stainless steels may also contain other element such as nickel, niobium, molybdenum, titanium, copper, manganese, silicon, nitrogen, phosphorus, and sulfur. When exposed to corrosive environment, the chromium in the steel combines with oxygen in the atmosphere to form a thin invisible layer of chromium oxide film. If the metal is cut or scratched and the passive film is disrupted, more oxide will quickly form and cover the exposed surface protecting it from corrosion. (Jonathan et al, 1999)

2.1.1 STAINLESS STEELS CLASSIFICATION

Generally stainless steels are classified according to their microstructure or predominant crystal phase, and are identified as ferritic, austenitic, martensitic, duplex, and precipitation hardenable.

2.1.1.1 FERRITIC STAINLESS STEEL

Ferritic stainless steel have low carbon content with chromium as the major alloying element.

The composition range: $C \leq 0.08\%$, $10.5\% \leq Cr \leq 30\%$ by weight.

It contains minor amounts of molybdenum, columbium and titanium. These grades of stainless steels are typically used where corrosion is not severe. They are good in stress corrosion cracking resistance and have good resistance to pitting and crevice corrosion in chlorine environments.

Ferritic stainless steels are magnetic at room temperature due to their body centre cubic crystal microstructure. Many of these stainless steel grades are subject to the precipitation of undesirable intermetallic phases when exposed to certain temperature ranges (www.weldingengineer.com, 19th October, 2011). These alloys have higher yield strength and low ductility than the austenitic stainless steels and are not hardenable by heat treatment like carbon steels; they exhibit a transition from ductile to brittle behavior as the temperature reduces especially in notch impact test (www.weldingengineer.com, 19th October, 2011). Nevertheless with or without nickel the ferritic stainless steels need engineering review for anything other than thin walled application as they are prone to brittle failure.

This grade of stainless steel represent about 25% of the total production and due to welding problems and low toughness properties compared to austenitic grade they are restricted to thinner gauges even if they are often the cost saving grade.

2.1.1.2 MARTENSITIC STAINLESS STEEL

Martensitic stainless steels are essentially alloys of iron and chromium that have a body centered tetragonal structure in heat treated conditions. The compositions of these alloys are specifically formulated to render them amenable to quench and temper heat treatment, in order to produce high level of strength and hardness. (Jonathan et al, 1999)

The chromium level of these alloys is between 11 and 18% which is almost the same as in some ferritic stainless steels. The higher carbon content in the martensitic grade result in complete transformation from δ-ferrite to austenite at high temperature (≈980°C) followed by a subsequent change to the hard martensite phase upon rapid cooling. (Jonathan et al, 1999)

Martensitic stainless steel is magnetic due to their crystal structure, they have smaller coefficient of expansion than the mild steels and their thermal conductivities are lower than those of mild steel. (Jonathan et al, 1999)

2.1.1.3 AUSTENITIC STAINLESS STEEL

Austenitic stainless steel remain the most popular grade of stainless steel, due to its unique combination of high ductility, high potential of strengthening weldability, toughness even at extra low temperature and of cause high corrosion resistance (www.arcelormittal, 18th Oct.2011)

This steel is alloyed with chromium and nickel, harden with cold work, but do not harden by heat treatment. They are non magnetic, possesses greater coefficient of expansion than the mild steels, but are inferior to steels of the martensitic group in terms of high stress applications.

Austenitic stainless steel in general contains 16% to 26% chromium, up to 35% nickel and has very low carbon content. Some of these steels are alloyed with minor amounts of molybdenum, columbium and titanium. They also exhibit a single phase, the face centered cubic (FCC) structure that is maintained over a wide range of temperatures. This structure results from a balance of alloying additions, primarily nickel that stabilizes the austenite phase from elevated temperatures to cryogenic temperatures (Jonathan et al, 1999).

The austenitic stainless steels were developed for use in both mild and severe corrosive conditions. They are used at temperatures ranging from cryogenic temperatures, where they exhibit high toughness, to elevated temperatures, where they exhibit good oxidation resistance.

Austenitic stainless steels are considered most familiar and most frequently used alloys in the stainless steels family (Jonathan et al, 1999).

2.1.1.4 DUPLEX STAINLESS STEEL

Duplex stainless steel is two phased alloys based on the iron-chromium- nickel system. These alloys usually comprise equal proportions of the body centered cubic (BCC) ferrite and face centered cubic (FCC) austenite phase in their microstructure and generally have low carbon content as well as molybdenum, nitrogen, tungsten, and copper. Typical chromium contents range from 20% to 30% by weight, nickel ranges from 5% to 10% by weight.

Duplex stainless steels solidify as 100% ferrite, but about half of the ferrite transforms to austenite during cooling through temperatures above 1040°C. This behavior is accomplished by increasing Cr and decreasing Ni content as compared to the austenitic grades.

Duplex stainless steels are ferromagnetic, a property that can easily differentiate them from common austenitic grades of stainless steels.

Generally the ratio of ferrite to austenite in duplex stainless steels depends mainly on the chemical composition, (www.weldingengineer.com, 19th Oct. 2011). The presence of ferrite with austenite provides better intergranular corrosion (IGC) resistance, other advantages offered by these alloys over convectional 300 series stainless steels are strength, chloride stress-corrosion cracking resistance, and pitting corrosion resistance.(www.weldingengineer.com, 19th Oct. 2011)

2.1.1.5 PRECIPITATION HARDERNING STAINLESS STEEL.

Precipitation hardening stainless steel contains between 11% and 18% chromium, 3% to 27% nickel, and carbon between 0.05% and 0.15%. They generally have better corrosion resistance than the martensitic stainless steels. They have high strength, which is due to precipitation hardening of a martensitic or austenitic matrix. Copper, aluminum, titanium, niobium and molybdenum are the primary elements added to these stainless steels to promote precipitation hardening.

These alloys are commonly categorized into three distinct types, namely; martensitic, semi-austenitic, and austenitic.

2.1.2 MICROSTRUCTURE OF STAINLESS STEEL.

The mechanical properties of stainless steels predominantly depend on the microstructure, which in turn depends on the phase transformation characteristic. (Balmforth et al, 2000)

At high temperature, austenite is formed, with a phase that has centered cubic crystal structure which dissolves 2% C and is soft and ductile. Under equilibrium cooling condition it will transform to ferrite and pearlite for the hypo-eutectoid steels or cementite and pearlite for hyper-eutectoid steels. Ferrite has a body centered cubic crystal structure which can hold only 0.025%C is also soft and ductile but not as the austenite (Pascoe, 1982).

Martensite is formed if the cooling rate is high, that suppresses the transformation of austenite to pearlite. This phase is hard, brittle, highly stressed internally and has a needle-like (acicular) appearance under the microscope (Dauda, 2008).

During solidification, duplex stainless steel first solidifies as ferrite. As the temperature decreases, austenite develops. For cast duplex, a structure of austenite islands in a ferrite matrix can be observed. For wrought alloys, the microstructure has morphology of laths of austenite in a ferrite matrix.

The microstructure in duplex stainless steel is usually composed of approximately equal amounts of austenite and ferrite. The austenite ratio can be increased to about 55-60% in order to improve the toughness and maintain a sufficient ratio in the heat affected zone (Charles, 1997). The desired microstructure is usually obtained by hot working, followed by solution annealing and quenching to ambient temperature (Charles, 1997). Hot working is usually performed in the temperature range 1000-1200°C (Gunn 1997 and Vannevik et al 1996).

When duplex stainless steels are subjected to temperatures from 350°C up to around 950°C, secondary precipitates form intermetallic phases, e.g. sigma phase, are formed in the 600-950°C temperature range. Ferrite is reformed at 350-525°C (embrittlement at 475°C). Ferrite reformation can have an embrittling effect and a negative impact on corrosion resistance. Hence unnecessary exposure to these temperatures must be avoided, (Gunn, 1997).

2.1.3 PHYSICAL PROPERTIES OF STAINLESS STEEL.

The average physical properties for each of the main groups of stainless steels are listed in table 2.1. This includes modulus of elasticity, density, coefficient of thermal expansion, thermal conductivity, specific heat, electrical resistivity, magnetic permeability and melting range. These values should be close enough for most of engineering purposes.

Table 2.1: Physical Properties of Some Stainless Steels

Property	Austenitic Grades	Ferritic Grades	Martensitic Grades	Precipitation Hardening Grades
elastic Modulus; 10^6 GPa (psi)	195(28.3)	200(29.0)	200(29.0)	200(29.0)
Density; g/cm^3(lb/in^3)	8(0.29)	7.8(0.28)	7.8(0.28)	7.8(0.28)
Coeff. Of Therm. Expansion; µm/m°C (µin/in°F)	16.6(9.2)	10.4(5.8)	10.3(5.7)	10.8(6.0)
Thermal conduct.; w/mk (Btu/hrft.°F)	15.7(9.1)	25.1(14.5)	24.2(14.0)	22.3(12.9)
Specific heat; J/kg °K(Btu/lb.°F)	500(0.12)	460(0.11)	460(0.11)	460(0.11)
electrical resistivity; µcm	74	61	61	80
Magnetic permeability	1.02	600-1100	700-1000	95
Melting Range °C(°F)	1375-1450 (2500-2650)	1425-1530 (2600-2790)	1425-1530 (2600-2790)	1400-1440 (2560-2625)

(Source: www.welding engineer.com)

2.1.4 MECHANICAL PROPERTIES OF STAINLESS STEEL

Metals can be fractured, bent, twisted, dented, scratched and otherwise damaged. With such widely varying properties, it becomes a problem to express in few words exactly what type of service a piece of metal can withstand without having the knowledge of its mechanical properties. (www.arcelormittalstainless.com, 19th Oct.2011)

The mechanical properties of stainless steel are those associated with the ability of the metal to resist mechanical forces and loads. These mechanical properties include strength, stiffness, elasticity, plasticity, ductility, brittleness, malleability, toughness, resilience, creep and hardness. These mechanical properties are directly linked to the carbon and nitrogen contents and microstructure. (www.arcelormittalstainless.com, 19th Oct.2011)

The austenitic stainless steel generally has higher tensile strength and elongation than the ferritic stainless steels but lower yield strengths. Reduction in area is about the same for both groups. Ferritic stainless steels generally have lower elongation at fracture and strain hardening properties than austenitic ones. As for plain carbon steels, ferritic stainless steels in the annealed state present a yield point followed by stress drop on the stress strain curves. (www.arcelormittalstainless.com, 19th Oct.2011)

Duplex stainless steels constitute an important stainless steel group which has found increasing use in recent years in engineering structures exposed to aggressive environments due to their excellent mechanical properties. This alloy displays properties characteristic of both austenitic and ferritic stainless steels.

The yield strength of duplex stainless steels is 2-3 times higher than that of 18Cr-10Ni austenitic stainless steels (Henrik et al, 2006), the ferrite usually contributes to the high strength, but the strength in duplex stainless steels is also higher than for pure ferritic stainless steels (Bennefois et al, 1991)). This can be explained by small grain size in duplex stainless steels

(Vannevik et al, 1996), caused by the mutual hindering of the growth of ferrite and austenite grains (Atamert et al, 1993), implying higher strength for the two phase structure than its constitutes.

The higher yield strength in duplex stainless steels is as a result of (Holmberg, 1994)

i. Presence of ferrite small grain size

ii. Formation of hard secondary austenite.

iii. Interstitial and substitutional solution hardening

2.1.5 ALLOYING ELEMENTS

The desired corrosion and mechanical properties of stainless steels are obtained by optimizing the balance of the important alloying elements. Emphases will be made on duplex grades.

a) Chromium

Chromium is the most important alloying element for stainless steel and a content of at least 12% is needed to create and maintain the passive film giving the material its corrosion resistance. Duplex grades normally contain relatively high levels of chromium, typically 20-29% to stabilize the ferrite phase. Coordinated additions of austenite-stabilizers, such as nickel or nitrogen, are required to maintain the phase balance. Chromium is beneficial for the resistance to both uniform and localized corrosion and decreases the pit propagation rate (Guha et al, 1984; Sakai et al, 1984). Chromium increases the pitting potential, the critical pitting temperature (CPT) and the critical crevice temperature (CCT), and improves the passive film stability in acidic environments.

There is a maximum limit to the chromium content of approximately 30-32%, where intermetallic phase precipitation can markedly reduce the ductility, toughness and corrosion resistance of these alloys.

b) Nickel

Nickel is a strong austenite stabilizer and a principal addition to austenitic stainless steels. Nickel alloying may decrease the resistance to crevice corrosion, and has been reported to be both beneficial and detrimental in pitting corrosion tests (Muira et al, 1990). In the duplex stainless steels, however, the main role of nickel is to maintain the ferrite-austenite balance, rather than modifying the corrosion resistance (Guha et al, 1984). Optimum nickel contents balance the chromium and molybdenum contents to give equal proportions of ferrite and austenite after solution annealing.

This appears to be most advantageous for the corrosion resistance, but also for the mechanical properties (Sakai et al, 1984). Low nickel levels can result in formation of a high proportion of ferrite and thereby decreased toughness. Nickel has also a positive effect on the impact toughness at low temperatures.

c) Molybdenum

Molybdenum is a ferrite-stabilizing alloying element with a strong beneficial influence on uniform and pitting corrosion resistance (included in the PRE) and on the passivation properties (Olson et al, 2003). Molybdenum content in excess of 3 or 3.2% has been reported to be required for high resistance to localized corrosion in acidic environments and to crevice corrosion in warm seawater (Sakai et al, 1984; Sridhar and Kolts, 1987). Molybdenum is favourable in most environments, but in strongly oxidizing environments, such as warm concentrated nitric acid and in hot alkaline solutions, grades containing molybdenum are less

resistant than alloys without molybdenum. The addition of molybdenum in duplex stainless steels should not exceed approximately 4% since it makes the material more susceptible to intermetallic phase precipitation by widening the **σ** phase field (Roscoe et al, 1986; Varol et al, 1992). Molybdenum has also been suggested to promote precipitation of α', which is responsible for the 475°C embrittlement of ferritic stainless steels and the ferrite phase of duplex grades.

d) Nitrogen

Nitrogen is an interstitial element that stabilizes the austenite and has strong influence on several properties. Nitrogen significantly increases the strength of the duplex grades, but may also improve the ductility and toughness of the alloy (Varol et al, 1992). Nitrogen has a strong beneficial influence on the passivity of stainless steels and is favourable for increasing the resistance of the base metal to pitting corrosion (included in the PRE), pit propagation, crevice corrosion, IGC and SCC (Tsuge et al, 1988; Liljas and Qwafort, 1986; Guha et al, 1984). Tsuge et al (1988) estimated that the nitrogen content required for achieving the same pitting resistance in both ferrite and austenite in 22Cr steels is approximately 0.18%. In base metals with lower nitrogen content, the austenite would be less resistant to pitting.

The beneficial effects of nitrogen have been reported to be further enhanced in the presence of molybdenum (Sakai et al, 1984; Truman et al, 1977). Nitrogen promotes the start of austenite formation at higher temperatures during the weld cooling cycle and the duplex grades contain up to 0.4% nitrogen to give improved austenite formation when welding (Ogawa et al, 1989). Nitrogen has been reported to reduce the elemental partitioning of chromium and molybdenum between the ferrite and austenite and at the same time, hinder intermetallic phase formation (Roscoe et al, 1986). The effect of nitrogen on the driving force for **σ** phase formation may, however, be smaller for duplex grades compared to that of the austenitic grades, because

nitrogen does not change the chromium activity as a result of a simultaneous change in phase fraction.

e) Manganese

Manganese stabilizes austenite and can partly replace nickel. Additions to stainless steel have been used to increase the solubility of nitrogen, which has a strong beneficial influence on pitting resistance. It has been reported that manganese itself may have a negative effect on pitting resistance, but combined additions of nitrogen and manganese override this effect (Roscoe et al, 1986). Replacing nickel with manganese and nitrogen also makes the price of the material more stable since the nickel price has fluctuated significantly in recent years. Examples include the low nickel lean duplex stainless steel LDX 2101 and the superaustenitic stainless steel 654 SMO

f) Other elements

Tungsten has become more commonly used as an alloying element in commercial stainless steels where it is used as a supplement to molybdenum for improved corrosion resistance (Roscoe et al, 1986). When used in the PRE expression, the factor for tungsten is approximately half of that for molybdenum because of higher atomic weight.

Tungsten has, however, also been reported to promote formation of intermetallic phases and cause a more rapid embrittlement than molybdenum (Charles, 1991). Copper is added to highly corrosion resistant austenitics such as AISI 904L and 254 SMO, and duplex grades such as Ferralium 255 (EN 1.4507, UNS S32550 and Zeron 100 (EN 1.4501, UNS S32760) to further improve the corrosion resistance in, for instance, reducing acids such as dilute sulphuric acid (Olsson, 2003). In most modern duplex alloys, carbon is limited to levels of 0.03% wt to

minimize the risk of formation of chromium carbides and thereby decrease the susceptibility of the duplex stainless steels to intergranular corrosion (Varol et al, 1992).

2.1.6 CORROSION RESISTANCE

Stainless steels are corrosion resistant due to formation of an invisible, 2-4 nm thick, passive film that is established in oxidizing environments when the steel contains at least 12% chromium. This film has the ability to be rebuilt by oxidation of the underlying metal when it has been damaged. There are, however, environments in which permanent breakdown of the passive layer occur either uniformly or locally, causing corrosion of the unprotected surface. Different media can cause different types of corrosion, which may vary in nature and appearance. Uniform corrosion or general corrosion occurs with an even corrosion rate over the whole surface that is exposed to the corrosive medium (often for the steel an aggressive acid e.g. hydrochloric acid or hydrofluoric acid). The corrosion rate is generally expressed as the material loss in mm/year and can thus be used as an estimation of the lifetime.

Selective corrosion can also occur in two phase materials such as duplex stainless steels. Different chemical compositions of the phases may lead to preferential attack at the weaker phase. Pitting corrosion most often occurs where chloride ions cause a local breakdown of the passive layer. The presence of halides, such as chlorides, in neutral or acidic solutions increases the corrosivity of both organic and inorganic acids. The solution becomes more aggressive at high chloride concentrations, low pH and high temperatures, but also small amounts of chlorides, 250 ppm, may affect the pitting corrosion resistance of stainless steels. One example is drinking water that can cause corrosion of stainless steel in domestic water heaters (Claes-Ove and Sven-Aven, 1995). The pits often appear to be rather small at the surface, but may have larger cross-section areas deeper inside the metal, (see Figure 2.1 below). Pitting corrosion is often more deleterious than uniform corrosion due to the rapid propagation rate and it is not

possible to circumvent the problem by dimensioning with thicker gauges as for uniform corrosion.

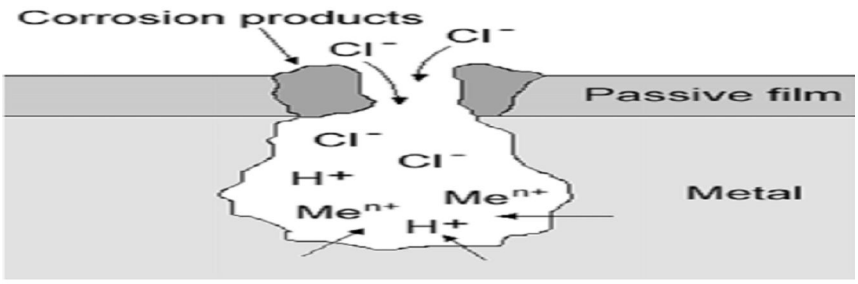


Figure 2.1 Principal cross-section of a corrosion pit (Charles,J. 1991).

As the attack is small at the surface and may be covered by corrosion products, pitting attack often remains undiscovered until it causes perforation and leakage. Crevice corrosion occurs under the same conditions as pitting, i.e. in neutral and acid chloride solutions. In the stagnant solution inside a crevice, the supply of new oxidant is restricted and crevices, such as those found at flanges or lap joints, are thus often the most critical sites for corrosion. High chloride concentrations and low pH increase the probability of pitting and crevice corrosion, as do high temperatures and stagnant solutions. Chloride induced stress corrosion cracking (SCC) is a brittle failure mode caused by the combined effect of tensile stress, including residual stresses in welds, and a corrosive environment. Most cases of SCC occur at temperatures above 50°C but failures at ambient temperature have occurred on standard grade austenitic steels, such as AISI 304L and AISI 316L in swimming pool atmospheres (Sridhar and Kolts, 1987).

Steels with a ferritic or duplex structure and high performance austenitic alloys generally display a very high resistance to SCC. lntergranular corrosion (IGC) occurs preferentially in chromium depleted grain boundaries as a consequence of precipitation of chromium carbides of M23C6 type in the HTHAZ subject to 550-850°C. In modern duplex and high alloy austenitic stainless steels, sensitization caused by chromium carbide precipitation is rarely a problem,

because of the low carbon content of these grades (Liljas, 1995). When chromium carbides appear, these are less harmful in duplex grades, since the ferrite allows a rapid healing of depleted zones compared to austenitics (Solomon and Devine, 1984). Titanium and niobium form carbides more easily than chromium and stabilized steels show good resistance to IGC even though their carbon contents may be fairly high. Low carbon grades and stabilized grades can be considered as equally resistant to IGC, unless exposed for long periods at temperatures above 500°C, in which case stabilized grades are to be preferred (Sridhar and Kolts, 1987).

When choosing a stainless steel for a certain application, it is important to consider all factors that can affect the corrosion resistance such as the environment, concentrations, pH, impurity content and the service temperature. Other factors that can have an effect on the performance of the product are weld defects, the presence of oxide from welding or heat treatment, contamination of the steel surface by particles of non-alloyed or low-alloyed steel, microbial activity, the presence of crevices and chlorination of water. More information about the corrosion performance of different stainless steels and the ability to withstand certain environments, concentrations, pH, etc. can be found in the Outokumpu Corrosion Handbook (Sridhar and Kolts, 1987).

2.2 WELDING PROCESS AND ITS CHARACTERISTIC

Welding is a process of joining two or more pieces of the same or dissimilar metals to achieve complete coalescence. This is the only method of developing a monolithic structure and it is often accomplished by the use of heat and or pressure, with or without filler metal (Palmer 2004). During this process, devices to obtain the necessary heat are used to fuse the joint faces in a controlled fashion. The most common welding processes used are:

i. Arc welding, which obtains heat from an electric arc and maintains it between two electrodes or between an electrode and the work piece.

ii. Oxy-fuel welding, here the heat is generated through the combustion of a fuel gas and oxygen to produce the heat required for joining.

iii. Resistance welding obtains the heat needed for welding from the resistance of the work piece to the electric current.

All welding processes must meet the following conditions (Dauda, 2008).:

i. Supply of energy to the joint interfaces to either make it plastic or molten.

ii. Avoidance of atmospheric contamination and its effects and the mechanism for the removal of these contaminants.

iii. Control of weld metallurgy.

2.2.1 WELDING PROCESSES

2.2.1.1. GAS TUNGSTEN ARC WELDING PROCESS [GTAW]

In the GTAW process, also known as the Tungsten Inert Gas (TIG) or Wolfram Inert Gas (WIG) process, the energy necessary for melting the metal is supplied by an arc struck and maintained by tungsten or tungsten alloy electrode and the work piece, under an inert or slightly reducing atmosphere. Stainless steels are always welded in the DCEN (Direct Current Electrode Negative) or DCSP (Direct Current Straight Polarity) mode. In these conditions, it is the workpiece that is struck by the electrons, enhancing penetration, while the electrode, which is generally made from thoriated tungsten (2%ThO_2), undergoes very little wear. If filler is employed, it is in form of either bare rods or coiled wire for automatic welding. The inert gas flows which protects the arc zone from ambient air, enables a very stable arc to be maintained.

Depending on the base material, shielding gas consists mainly of mixtures of argon (Ar), helium (He) and hydrogen. The common workpiece thickness ranges from 0.5mm to 3.5/4.0mm. (Pierre, 2007)

2.2.1.2. GAS METAL ARC WELDING [GMAW]

In the GMAW process, also known as MIG (Metal Inert Gas) process, the welding heat is produced by an arc struck between a continuously fed metal wire electrode and workpiece.

Contrary to the GTAW and PAW processes, the electrode is consumable; an arc is being struck between fusible filler wire and the workpiece under a shielding gas.

The essential characteristics of this process are:

i. The use of very high current densities in the electrode wire (>90A/mm^2), about 10 times higher than in the covered electrode [SMAW] process.

ii. Rapid melting of the electrode wire [melting rate of about 8m/min) due to the high temperature of the arc, making it necessary to use an automatic wire feed system, supplied by a 12kg spool.

iii. Stainless steels are always welded in Direct Current Electrode Positive (DCEP) or Direct Current Revise Polarity (DCRP) modes, the positive pole of the generator being connected to the electrode.

iv. The welding torch is generally held manually (so called 'semi automatic' process)

The mechanism of metal transfer in the arc being an important process parameter can be done in three principal modes (Pierre, 2007)

i. The short circuiting or dip transfer mode, in which the metal melts to form large droplets whose diameter is often greater than that of the wire. As the droplet forms at the end of the electrode, it makes contact with the weld pool and creates a short circuit, with a sudden increase in current. The surface tension causes a pinching effect which separates the droplet from the electrode. The frequency of this phenomenon is of the order of 20 to100 Hz, corresponding to cycle times between 0.01 and 0.05 seconds.

ii. The globular transfer or gravity transfer mode; as in the previous case the melting occurs in the form of large droplets, which break away when their mass is sufficient to overcome surface tension forces and due to the greater arc length, fall freely before coming in contact with the weld pool.

iii. The spray transfer mode, involves current densities above a certain transition level, of order of 200A/mm^2. The electrode melts to give a stream of fine droplets. As the current density increases further, the electrode tip becomes conical and the stream of even finer droplets is released axially.

GMAW requires a shielding gas to prevent oxidation in the welding arc. Argon with 2% oxygen (O_2) gives a stable arc and is suitable for most applications. Argon with 3% carbon dioxide (CO_2) gives about the same result. The welding speed and penetration can sometimes be enhanced when He and Hydrogen are added to the argon + Oxygen or argon + CO_2 shielding gas. Gases higher in CO_2 tend to produce significant carbon pick up by the weld pool together with chromium oxidation. It is for this reason that they are not recommended. See section 2.4.2 for more on selection of welding gas. (www.praair.com)

The bead size and extent of penetration vary with the workpiece grade, the type of joint, the transfer mode and the skill of the welder. For V joints and square butt joints welded in one run, the common workpiece thickness range is 1.0mm to 5.0mm. (Pierre, 2007)

2.2.1.3. SHIELD METAL ARC WELDING [SMAW]

This process also known as manual metal arc [MMAW] is a very old process. Since its first applications were reported in 1907 by Kjelberg, it remains widely used due to its great flexibility and simplicity. The electrode consists of a metal core covered with a layer of flux. The core is usually a solid stainless steel wire rod. The covering, which plays an essential role in the process, is extruded onto the core, and gives each electrode its specific personality. It serves three main functions: electrical, physical and metallurgical. The electrical function is the initiation and stabilization of the arc, while the physical action concerns the viscosity and surface tension of the slag, which control the transfer of metal droplets, the effective shielding of the weld pool and its wetability. The metallurgical role involves chemical exchanges between the weld pool and the slag, i.e. refining of the weld metal. (Pierre, 2007)

The covering contains calcium carbonate ($CaCO_3$) which dissociates in the arc at about 900°C, to form CaO and CO_2, the latter ensuring protection of the arc zone

$$CaCO_3 \rightleftharpoons CaO + CO_2$$

The common workpiece thickness range is:

- 1.0mm to 2.5mm [for single run processes]
- 3.0mm to 10.0mm [for a multiple pass technique). (Pierre, 2007).

2.2.2 SELECTING SHIELDING GASES FOR WELDING OF STAINLESS STEELS

At high temperature, all metals commonly used for fabrication will oxidize. Every welding process provides shielding from the atmosphere by some method. In the oxy-fuel process, the weld pool is shielded from the atmosphere by the combustion by-product of carbon monoxide (CO) and carbon dioxide (CO_2).

In stick welding (SMAW), the CO and CO_2 are also the shielding gases.

Submerged-arc welding shields the puddle by a different method. As the puddle progresses, the intense heat melts the flux in the joint area; this forms a slag that covers the weld and excludes the atmosphere.

GMAW (MIG) and GTAW (TIG) are both gas shielded processes in which the shielding gas is provided from an outside source. No fluxing agents are included in the filler metal of solid wires.

The choice of shielding gas has a significant influence on the following factors. (Pierre, 2007):

i. Shielding efficiency (controlled shielding gas atmosphere).

ii. Metallurgy, and mechanical properties (loss of alloying elements, pickup of atmospheric gases).

iii. Corrosion resistance (loss of alloying elements, pickup of atmospheric gases, surface oxidation).

iv. Weld geometry (bead and penetration profiles).

v. Surface appearance (Oxidation, spatters).

vi. Arc stability and ignition.

vii. Metal transfer.

viii. Environment (Emission of fumes and gases).

2.3 WELDING CONSIDERATIONS FOR DUPLEX STAINLESS STEEL

2.3.1 WELDING METALLURGY

As welding is an important method in castings upgrading and fabrication, to weld duplex stainless steel, it is important to understand how duplex stainless steels transform at different cooling rates, the effect of peak temperature in the HAZ and filler metal dilution.

2.3.2 HEAT AFFECTED ZONE (HAZ)

The HAZ is the area of the base metal that has its microstructure and properties altered by inducing intensive heat into the metal. The HAZ should have corrosion resistance and impact toughness comparable to the base material minimum requirements. Duplex stainless steel and super duplex stainless steel exhibit a narrow-HAZ, in comparison to austenitic stainless steels, due to the low heat input welding processes and the high thermal conductivity of the material. (www.stainlesssteel.net)

The HAZ experiences a range of thermal histories with peak temperatures from ambient to the solidus, adjacent to the weld. With fairly rapid heating and cooling, and in multi-pass welds, repeated exposure to elevated temperatures, the total thermal cycle at any one point in the HAZ is often complicated. Thus, acquiring an understanding of metallurgical consequences in terms of ferrite/austenite balance, precipitation of secondary phases, grain growth and the width of the HAZ, all of which consequently affect mechanical properties and corrosion resistance of the steel, is of vital importance.

2.3.3 WELD FUSION ZONE (FZ)

Weld fusion zone technically refers to the area of coalescence produced by the welding process. This is produced by melting of a part of the base metal in addition to the electrode/filler materials used or in another word it is an admixture of the base metal and, if used, the deposited filler metal (Dauda, 2008) . Since a weld metal is similar to a casting, it will exhibit segregation of alloying elements. However, the primary solidification phase with duplex steels is normally ferrite, and this causes minimmum segregation of chromium and molybdenum during

solidification. Moreover, diffusion rates are high at temperatures just below the melting point, and homogenization of alloy elements in the ferrite can take place [Gooch,1991].

The situation regarding partitioning of elements between ferrite and austenite upon solid state transformation during a welding cycle is complex. Depending on the heat input, the composition and corrosion resistance of the ferrite and austenite phases can vary. At low heat input, the ferrite-austenite transformation is controlled by nitrogen, and thus there may be little difference between the substitutional element contents of the two phases on cooling to room temperature, although nitrogen will be enriched in the austenite. At high heat input, there is sufficient time for diffusion of Cr, Mo and Ni to occur, and thus there may be significant differences in final alloy content between two phases [Gooch,1991 and Liljas,1994].

Welding without the addition of filler material or excessive dilution with basemetal should be avoided unless postweld solution annealing is to be performed [Kokawa et al 1995].

Duplex stainless steels are often welded with overmatching filler metals, which usually contain at least a 2% higher nickel content than the base metal

2.3.5 WELDABILITY

Weldability means the relative ease of producing a defect-free weld with adequate mechanical properties and corrosion resistance. The principal defects of interest are hot cracks (fusion zone or heat affected zone hot cracking) and cold cracks (hydrogen assisted cracking).

2.3.6 FILLER METAL

Filler metal selection is critical to maintaining the mechanical and corrosion properties of the weld and HAZ. In the fusion zone of GTAW, the microstructure can be significantly high in ferrite, resulting in poor toughness and corrosion resistance. Autogenous welds are not applied for part without a post-weld solution treatment.

The use of matching filler metal generally does not improve the situation, due to the dilution effect, which results in high ferrite levels in the weld. Like autogenous welds, welds

with matching filler metal should receive a postweld solution treatment [Taylor, 1994, and Holmberg, 1994]. Filler metals that have a modified chemistry compared to the base metal are generally accepted. The filler metal chemistry is modified to provide comparable mechanical properties and better corrosion resistance and to allow for the loss of particular elements in the arc [Taylor, 1994]. To accomplish the above goals, filler metals are higher in nickel and contain nitrogen.

2.3.7 HEAT INPUT

Heat input is a very important factor for welding of duplex stainless steel because this energy input controls the overall cooling for adequate austenite formation in the welds. Too low a heat input will result in excessive ferrite thus reducing toughness, corrosion resistance and increasing materials susceptibility to hydrogen embrittlement. On the other side, too high a heat input would result in a slow cooling rate; which may cause formation of secondary phases like **σ** phase, thus reduce toughness and corrosion resistance. A practical limit for DSS is provided by the cooling time between 1200 and 800°C, as it covers the temperature range over which austenite formation occurs. Preferred cooling is approximately 4 to 15 seconds, which correspond to a cooling rate of 20-50 °C/s (Gunn, 1997)

The heat input range can be maintained for each grade of duplex stainless steel, for example 22%Cr grades, 0.5-2.5kj/mm are recommended for 10-15mm thickness (www.steel.sandvik.com, 17 Oct. 2011 and www.metrode.com 19th Jan.2012).

2.3.8. PREHEAT AND MULTI-PASS

In case of multi-pass welding, usually, preheat is not necessary for DSSs. Preheat and interpass temperature should be always lower than 150°C (300°F) to adjust heat input and control the formation of ferrite austenite or secondary phases. However, the maximum interpass temperature depends on the grade and arc energy employed (Gunn, 1997). It is recommended

that interpass temperature for SAF 2304 and SAF 2205 shall be maximum 480^0F, and SAF 2507; 300°F (www.steel.sandvik.com).

2.4 REVIEW OF PAST WORK

Labanowski and Krzysztofowicz (2005) studied the influence of welding thermal cycles on corrosion resistance of duplex stainless steel. The susceptibility of the heat affected zone (HAZ) of duplex stainless steel weldments to stress corrosion cracking was investigated. Corrosion tests were performed with the use of the slow strain rate test technique in boiling $MgCl_2$ corrosive environment and concluded that,

i. The structure of the HAZ of the welded joint of 2205 duplex stainless steel strongly influence the stress corrosion cracking susceptibility when subjected to slow rate test in boiling $MgCl_2$ solution.

ii. The deterioration of stress corrosion cracking resistance was observed when less than 40% of austenite existed in the HAZ structure.

iii. The fracture surface changed from ductile for samples tested in an inert environment through mixed, ductile brittle for HAZ structure containing over 30% of austenite to fully brittle for HAZ structure where little amounts of austenite existed .

iv. Cracks were propagated along ferrite/austenite interfaces or transgranular through ferrite grains.

Nowacki, and Rybicki (2007), worked on the corrosion resistance of SAW duplex stainless steel joints welded with high heat input. Their aim was to find out if the welding heat input exceeding the recommended value (2.5kJ/mm) will have any negative impact on the strength of the executed welded joints as well as description of influence of the heat input of submerged arc welding of duplex stainless steel UNS S31803 on welded joint microstructure,

particularly average value of ferrite volume fraction, mechanical properties and corrosion resistance. The exceeded heat inputs used were 3.0kJ/mm,3.5kJ/MM,4.0kJ/mm, 4.5kJ/mm and 5.0kJ/mm. Their findings were based on the performed tests and their conclusion is that according to DNV Rules, the welding heat input exceeding the recommended values has no negative impact on the strength properties and corrosion resistance of the executed joints. It also showed that submerged arc welding of duplex stainless steel with heat input from2.5kJ/mm up to 5.0kJ/mm has no negative influence on the properties of the joints.

Labanowsk (2007), worked on the mechanical properties and corrosion resistance of dissimilar stainless steel welds, the purpose of his work was to determine the influence of welding on microstructure, mechanical properties, and stress corrosion cracking resistance of dissimilar stainless steels butt welded joints. Duplex 2205 and austenitic 316L steels were used. Butt joints of plates 15mm in thickness were performed with the use of submerged arc welding (SAW) method. The heat input was in the range of 1.15 – 3.2 kJ/mm. various plates' edge preparations were applied. Microstructure examinations were carried out. Mechanical properties were evaluated in tensile tests, bending tests and Charpy-V toughness tests. Susceptibility to stress corrosion cracking was determined with the use of slow strain rate tests (SSRT) performed in inert (glycerin) and aggressive (boiling 35% MgCl2 solution) environments. He found out that all tested joints showed acceptable mechanical properties. Metallographic examinations did not indicate the excessive ferrite contents in heat affected zones (HAZ) of the welds. It was shown that area of the lowest resistance to stress corrosion cracking is heat affected zone at duplex steel side of dissimilar joins. That phenomenon is connected with undesirable structure of that zone consisted of greater amounts of coarse ferrite grains and acicular austenite precipitates. High heat inputs do not deteriorate mechanical properties as well as stress corrosion cracking resistance of welds.

Afolabi and Borode (2007), worked on the stress corrosion cracking behavior of medium carbon steel in caustic soda, potash and a mixture of the two regents. This was done by fracturing the material on a tensometer after every seven days of immersion in the media. Percentage elongation and percentage reduction in cross-sectional area were used to investigate the stress corrosion cracking of the steel. The result obtained showed that medium carbon steel is susceptible to SCC in both caustic soda and potash media. Carbon cracking caused intergranular SCC in both media due to retained internal stresses in the steel while hydrogen cracking also occurred in caustic soda medium. Medium carbon steel was found to be more susceptible to SCC in caustic soda medium than potash solution.

Afolabi (2007), carried out investigation on corrosion and stress behavior of low and medium carbon steels in cassava and cocoa extracts by weight loss measurement and constant extension to fracture method respectively. The results obtained showed that medium carbon steel is more susceptible to corrosion than low carbon steel in both media. SCC is also more in medium carbon steel than low carbon steel in the two media under study. These deductions are due to higher carbon content in medium carbon steel coupled with various aggressive corrosion constituents contained in these media. Hydrogen embrittlement, as well as carbon cracking, is responsible for SCC of these materials in the agro-fluid media.

CHAPTER THREE

MATERIALS, EQUIPMENT AND METHODS

3.1 MATERIALS AND EQUIPMENT

3.1.1 MATERIALS.

Duplex stainless steel was the main material used for this research which was sourced locally at Jos building materials market, while its chemical composition was determined at the National Metallurgical Development Center Jos using the XFR test. Other materials that were used are: lubricating oil 85W90, neem oil, electrode E308L-16 and Nertalic 50 which has higher nickel content than the base metal, and etchant (10ccHCl, 3cc NHO_3 and 100cc distilled water) .

3.1.2 EQUIPMENT

The following items of equipment were used for the research work,

i) Denison tensometer, 500KN max capacity, model No: T42B2.

ii) Izod impact machine, type-6701

iii) Indentec hardness testing machine, 81287.5KVL model:B

iv) Lathe machine model: TUG-40

v) Gas metal arc welding machine, model:Synergic PRO MIG 475

vi) Mosa Shield metal arc welding machine, model: TS 615 VS-BC

vii) Scanning Electron Microscope. Model:EVO MA-10 manufactured by Carl,

viii) Gemco Heat furnace model: 40/90/40, power:20KW

ix) Infrared thermometer, Autopro Raytek Model:465-9173

3.2 METHODOLOGY

3.2.1 PRE-WELDING SAMPLE PREPARATION.

The duplex stainless steel was cut into equal pieces (samples) of length 100.2mm; they were further cut into two equal parts then joined together using different welding processes and subjected to different treatments, while some samples served as standards for comparison and analysis.

All the samples for welding were each chamfered to produce 30° half groove angle on one side with the aid of a milling machine, leaving a root face of 2mm each. The butt joint welding method was implemented as illustrated in fig 3.1

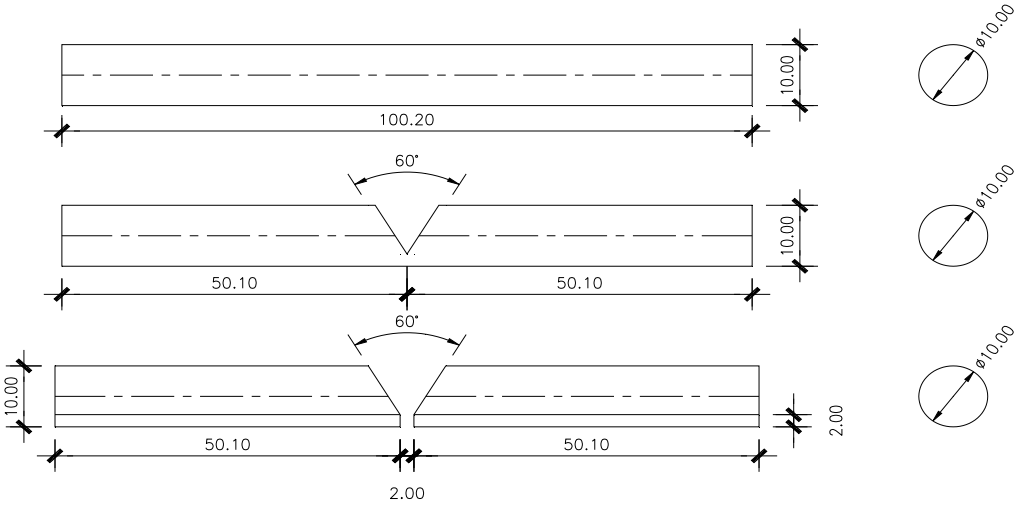


Fig 3.1 joint preparation for V-groove welding

Samples were cleaned of dirt and oil and a grinding machine was used to grind the surfaces of samples prior to welding in order to have smooth and uniform surfaces.

3.2.2 Welding procedure.

The gas metal arc welding and shield metal arc welding processes were used to weld over one hundred samples respectively. They were laid on an angle bar with their beveled edges parallel and facing each other, leaving a root face and root opening of 2mm with an included angle of 60° then an arc was struck. The first bead was laid down at the root of the joint to ensure equal fusion in both rods. Before the second bead was laid, the first bead was allowed to cool to about 150°C. In case of SMAW, any slag noticed was removed before an additional bead was laid. The welding parameters are shown in table 3.1. The number of passes used was two on each of the sample; the second pass was to fill the grove and to produced a crown as shown in fig3.2.

Both welded samples were cleaned of dirt and oil. The grinding machine was used to grind the surfaces of samples after welding in order to have smooth and uniform surfaces.



Fig3.2 welded sample

3.2.3 Post-welding heat treatment.



Fig 3.3 Gemco furnace (from I D C Zaria)

Two post heat treatments were adopted viz:

i) Stress relieve annealing

ii) Hardening by quenching and tempering

3.2.3.1 Stress-Relieve annealing

This treatment was done by heating the samples from ambient temperature up to 600°C, and then soaked at this temperature for 30 minutes. After which they were removed from the furnace and air cooled back to ambient temperature.

3.2.3.2 Quenching and tempering.

Samples, that had been previously stress relieved were again heated to the temperature of 900°C and soaked at this temperature for 30 minutes, they were then quickly removed and quenched into a can of engine oil or Neem oil at room temperature.

The quenched samples were tempered slowly by reheating them to 300°C and allowed to soak for 30 minutes, after which they were removed from the furnace and allowed to cool to room temperature in air.

3.3 Mechanical test procedure

3.3.1 Tensile strength test.

Tensile strength indicates the ability of a material to withstand forces that pull it apart as well as the capability of the material to stretch prior to failure. Tensile tests were carried out using a Denison Tensometer, with maximum load of 500KN at the Mechanical Engineering Department of Ahmadu Bello University Zaria. Samples were prepared according to the Fig. 3.4 below (BS18 standard). The test specimen size was 102.2mm length and a diameter of 10mm of which a gauge length 50mm was marked on all test samples (i.e. the weld joint in the center of the gauge length). The samples were mounted by their ends attached unto the holding grips of the upper and lower jaws of the testing machine. A dial gauge was fixed at the lower jaw.

During the test, the load was increased until fracture occurred. Both the load and the corresponding elongation on the samples were read off from the machine at intervals of 2KN. The final load and elongation were read off at failure.

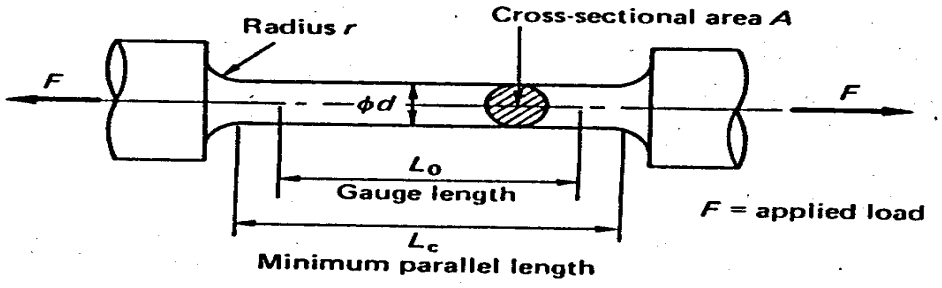


Fig 3.4 Standard sample for tensile test

Proportional sample (BS18) are given by the relationship

$L_O=5.56\sqrt{A}$. Since $A=\pi d^2/4$, then $\sqrt{A}=d\sqrt{\pi}/2=0.88d$. Thus $L_O=5.65X0.88d\approx 5d$

3.3.2 Charpy Impact test

Impact strength of the samples was determined by using the Charpy V notch test method. All the samples to be tested were notched at the centre to about 2mm depth. Charpy impact tests were conducted in accordance with ASTM A370 "Standard Methods and Definitions for Mechanical Testing of Steel Products", and ASTM E23, "Standard Method for Notched Bar Impact Testing of Metallic Materials". The Charpy V-notch samples, used in this evaluation, were machined according to the specification in ASTM E23 as shown in Fig 3.5.

Charpy impact testing follows the procedure of ASTM E23:

a) The energy indicator of the Charpy machine was set at the maximum reading.

b) The sample bar was placed in the proper position on the sample anvils

c) The pendulum was then released smoothly. The value on the indicator was then recorded.

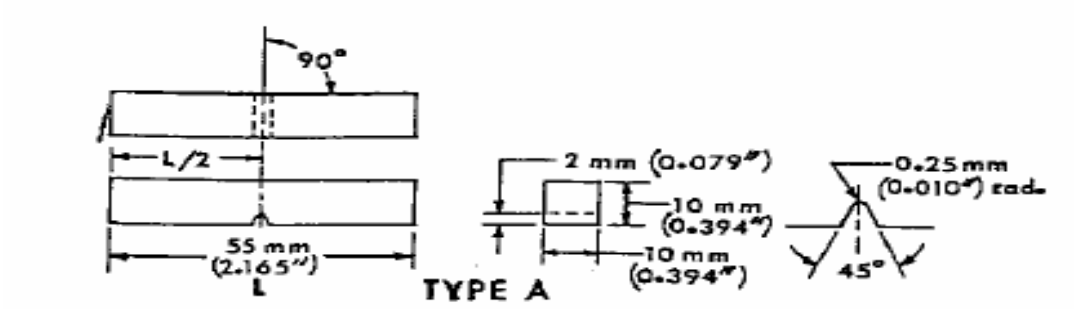


Fig 3.5 standard sample for charpy impact test

3.3.3 Hardness Test.

The hardness values of the samples were determined according to the provisions in ASTM E18-79 using the Rockwell hardness tester with a 120° diamond indenter, minor load of 10Kgf, and major load of 60Kgf. Before the test, the mating surface of the indenter, plunger rod and the test samples were thoroughly cleaned by removing dirt, scratches and oil.

Each sample was placed on the anvil, which acted as a support for the test sample. A minor load of 10Kgf was applied to the sample in a controlled manner without inducing impact or vibration and a zero datum position was established, after that a major load of 60Kgf was applied, the reading was immediately taken when the pointer comes to rest or had slowed appreciably and dwelled for up to 2 seconds. The load was then removed and the hardness value was read directly from the semi automatic digital scale. Indentec universal hardness testing machine 8187.5 KVL model B was used for the test at the Metallurgical Department of Ahmadu Bello University Zaria.

3.4 Microstructural Analysis

3.4.1 Surface preparation

The surface of samples for metallographic examination were ground and polished. The grinding process was performed using silicon carbide emery cloth of varying grits starting with the coarsest grit size of 120. Subsequently grit sizes 240, 320, 400 and 600 were used. The grinding was done wet with the aid of uni-cut soluble oil as a lubricant. The lubricant was applied intermittently to prevent overheating of the sample and to provide a rinsing action to flush away the particles being removed from the surface.

Polishing was carried out using a silicon abrasive in form of a very fine powder (1000 grit). The powder was applied to a wet polishing wheel rotating in the clockwise direction. This resulted into shiny, scratch free surfaces ready for etching and microscopy. Before etching the samples were rinse in detergent "omo'' to remove all particles on their surface.

3.4.2 Etching

Etching was done to expose and make visible the grains of the samples under the different conditions of heat treatment, as received and as welded. The etching was done using 10cc of HCl, 3cc HNO_3 and 100cc distilled water.

3.4.3 Scanning Electron Microscope Analysis

Samples after preparation were attached to multi-stub sample holder with the use of double sided conductive aluminum tape, after which, they were mounted onto the sample chamber, while the column was put at vacuum. After reaching the vacuum target, the electron gun was switched on which passed an accelerating voltage of 20kV and probe current of 227pA through the samples at a working distance of 7.0mm and 6.0mm.

Micrographs of the Samples were taken at two different positions viz; the fusion Zone (FZ) and the heat affected Zone (HAZ). The scanning electron microscope (SEM) EVO MA-10 manufactured by Carl, was used for the analysis at Sheda Science and Technology Complex, Abuja.

3.5 Samples Labeling

The samples after preparation were labeled as follows before testing them; this was also referred to during the discussion of results.

Table 3.1 sample labeling.

Sample A	Sample that was welded with GMAW method without heat treatment
Sample A_1	Sample that was welded with GMAW and quenched in neem oil (heat treated)
Sample A_2	Sample was welded with GMAW and quenched in engine oil(heat treated)
Sample A_3	Sample that was welded with GMAW and undergo stress relief heat treatment
Sample B	Sample that was welded with SMAW method without heat treatment
Sample B_1	Sample that was welded with SMAW and quenched in neem oil (heat treated)
Sample B_2	Sample that was welded with SMAW and quenched in engine oil (heat treated)
Sample B_3	Sample that was welded with SMAW and undergo stress relief heat treatment
Sample C	As received

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

4.1.1 Chemical Composition of Research Material

X ray florescence test was used to determine the actual chemical composition of the research material. Table 4.1 shows the results of XRF test carried out on the material as received from the manufacturing company.

Table 4.1: Research Material Chemical Composition

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Al
%by wt	0.02-0.05	0.238	1.57	0.036	0.032	>9.96	>6.60	0.342	0.011
Element	V	W	Pb	B	Sn	Zn	As	Bi	Ca
%by wt	0.106	0.036	>0.003	<0.0005	0.012	0.029	<0.001	0.009	0.0015
Element	Cu	Co	Ti	Nb	Ce	Zr	La	Fe	
%by wt	0.302	0.132	0.011	0.046	0.031	0.0015	0.0043	69.6	

The result in table 4.1 shows that the material is actually a duplex stainless steel. This is due to the presence of high percentage composition of iron (Fe) as the base material, chromium (Cr) and nickel (Ni) as major alloying elements, low percentages of Carbon (C) and other elements.

4.1.2 Scanning Electron Micrograph of the Samples

The micrographs of the samples, as taken by scanning electron microscope, are presented in plates 4.1 to 4.17.

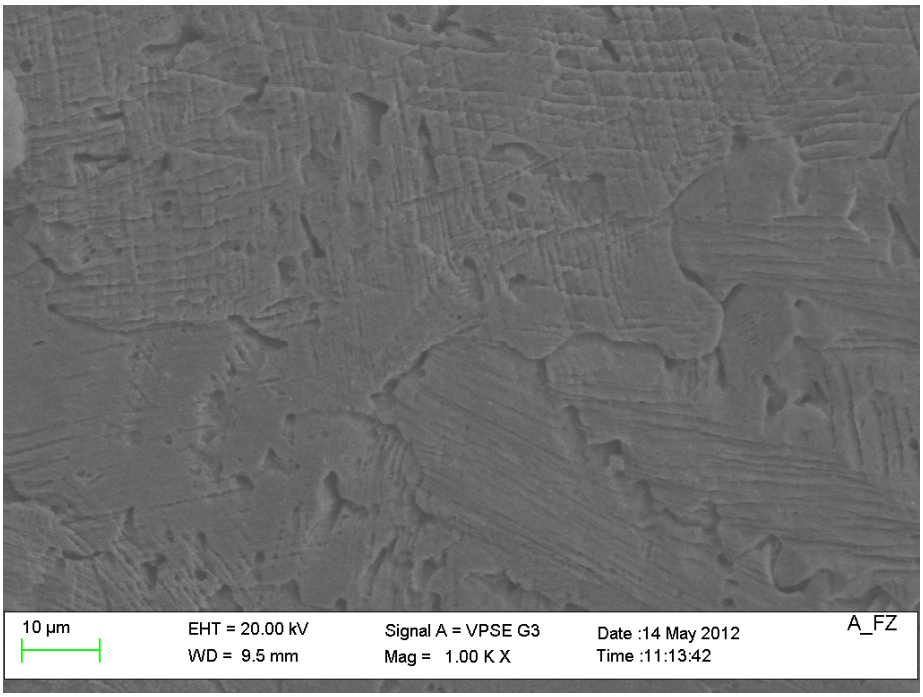


Plate 4.1: Micrograph of the Fusion Zone for Sample A

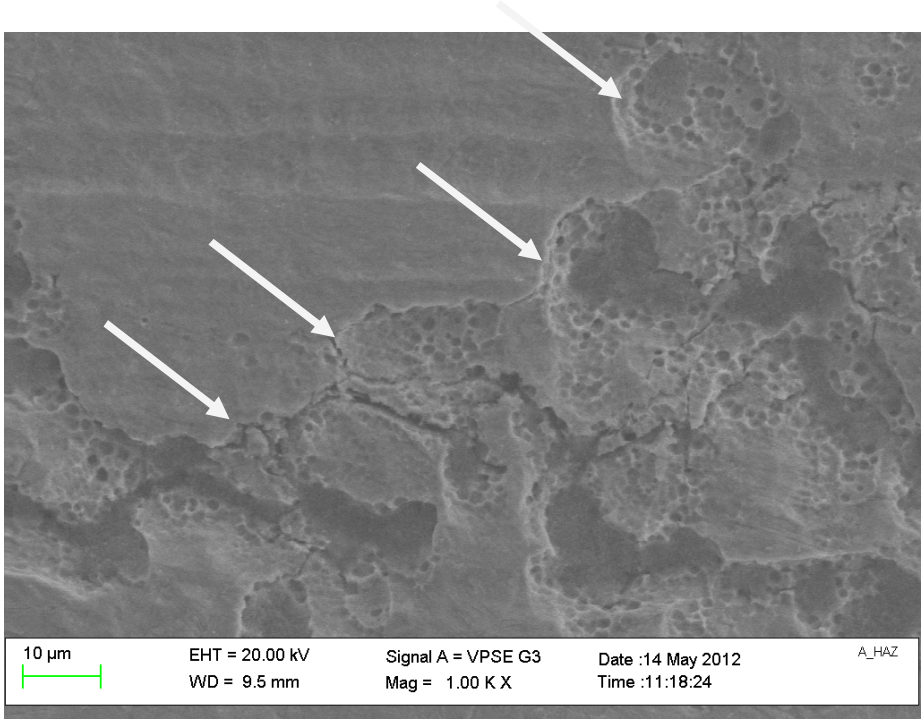


Plate 4.2: Micrograph of the Heat Affected Zone for Sample A

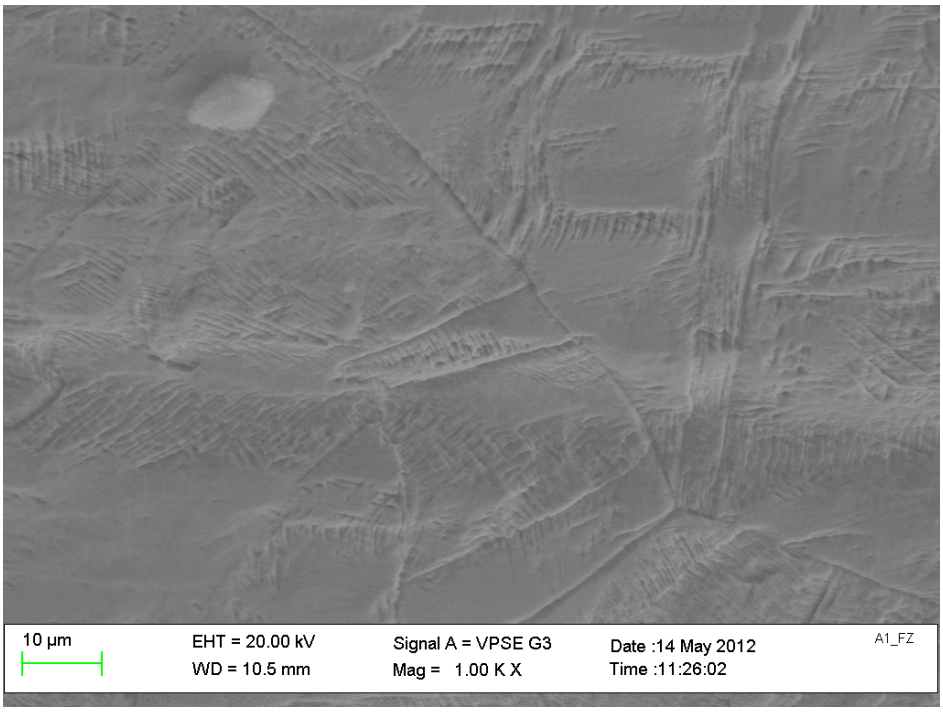


Plate 4.3: Micrograph of the Fusion Zone for Sample A1

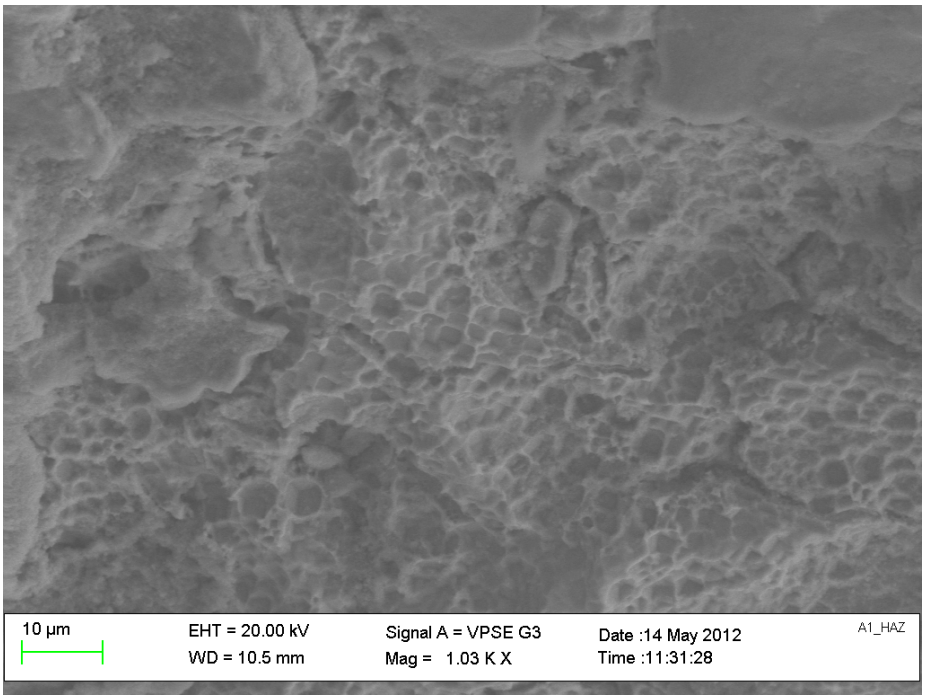


Plate 4.4: Micrograph of the Heat Affected Zone for Sample A1

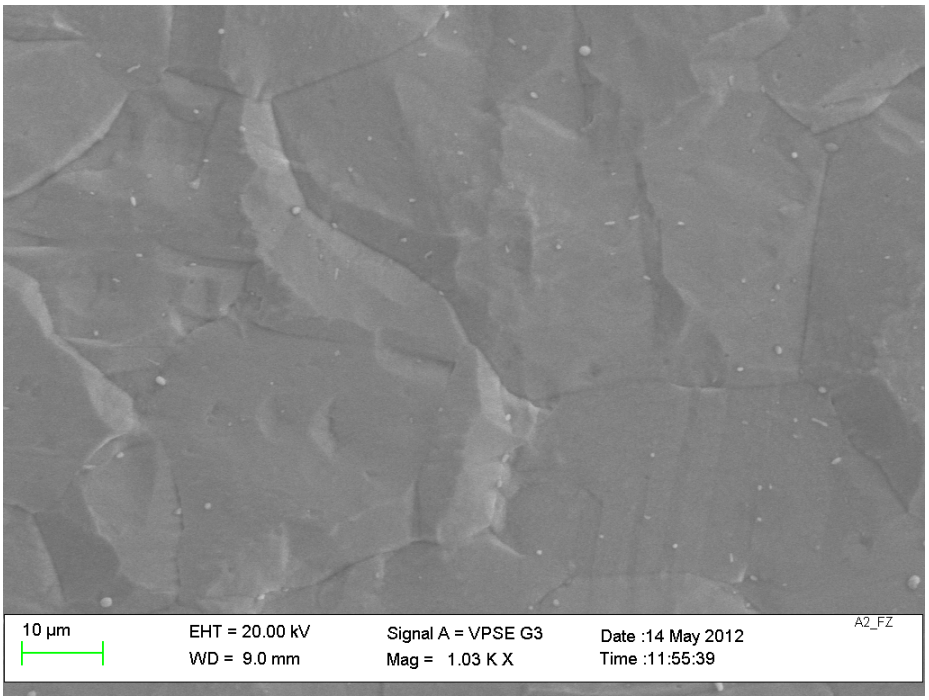


Plate 4.5: Micrograph of the Fusion Zone for Sample A2

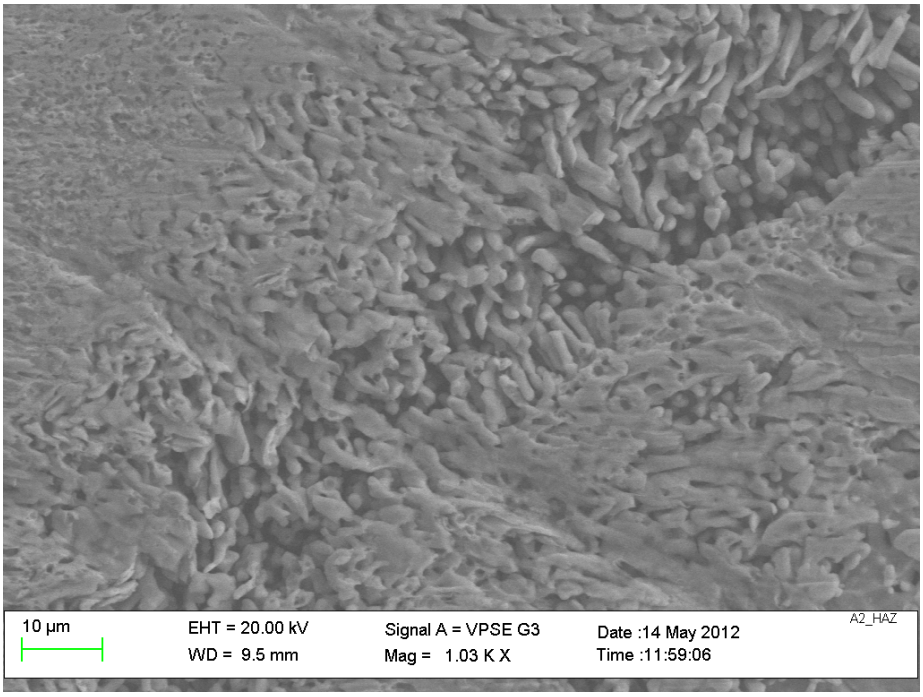


Plate 4.6: Micrograph of the Heat Affected Zone for Sample A2

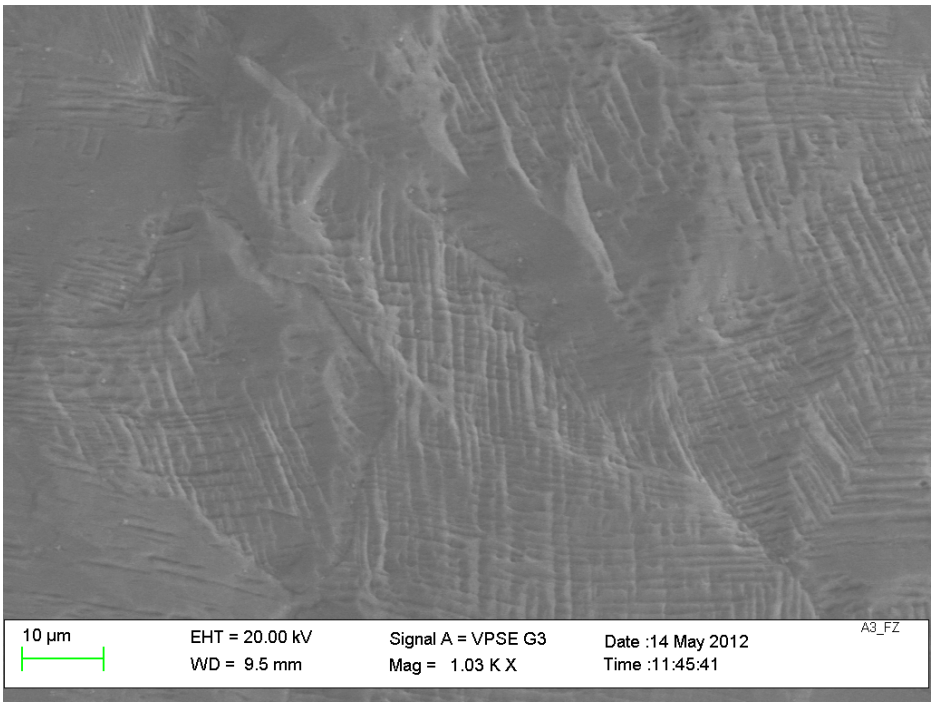


Plate 4.7: Micrograph of the Fusion Zone for Sample A3

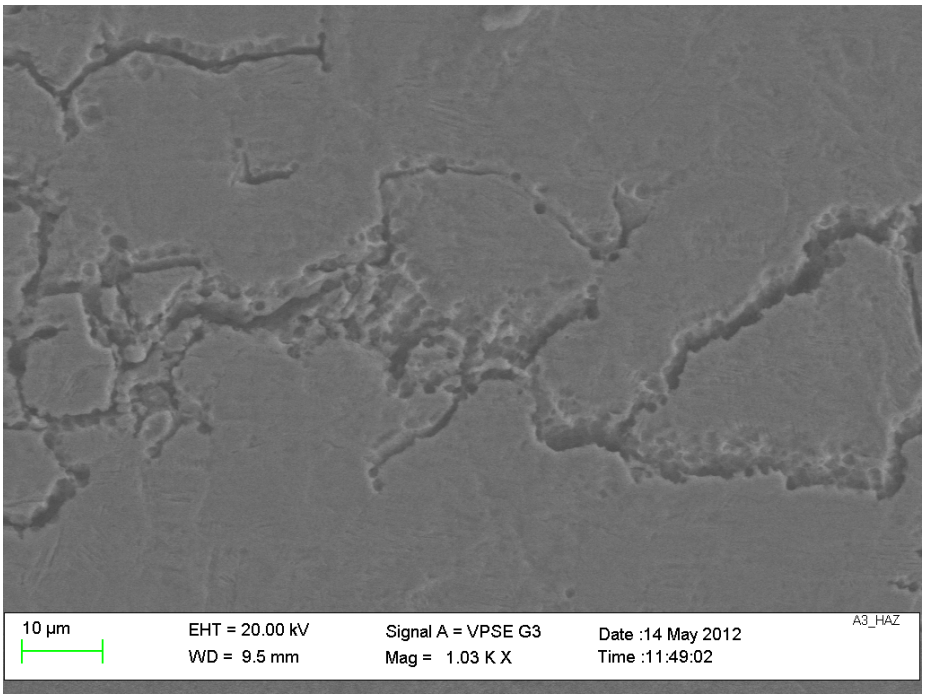


Plate 4.8: Micrograph of the Heat Affected Zone for Sample A3

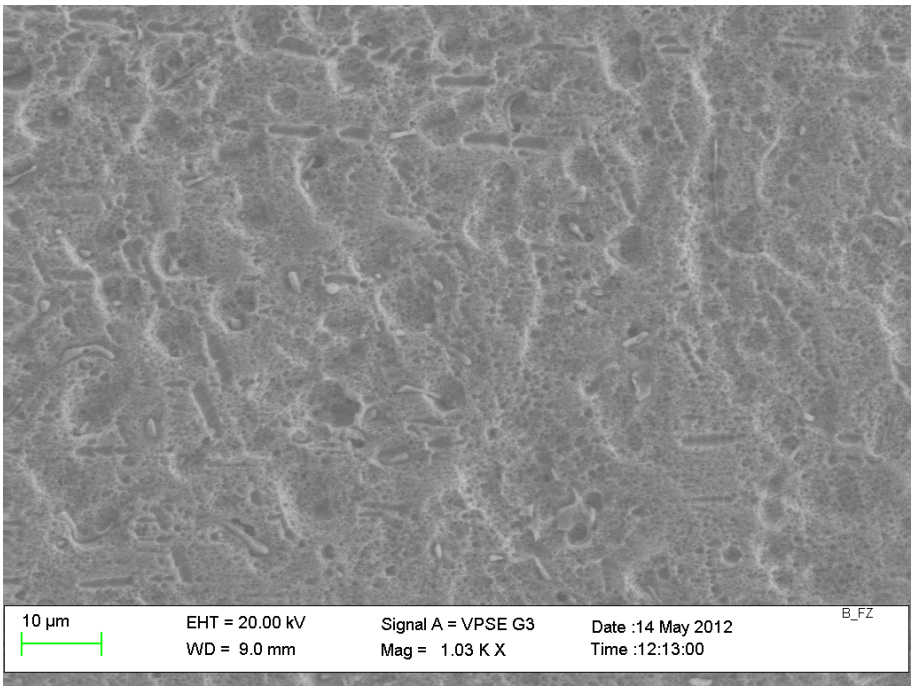


Plate 4.9: Micrograph of the Fusion Zone for Sample B

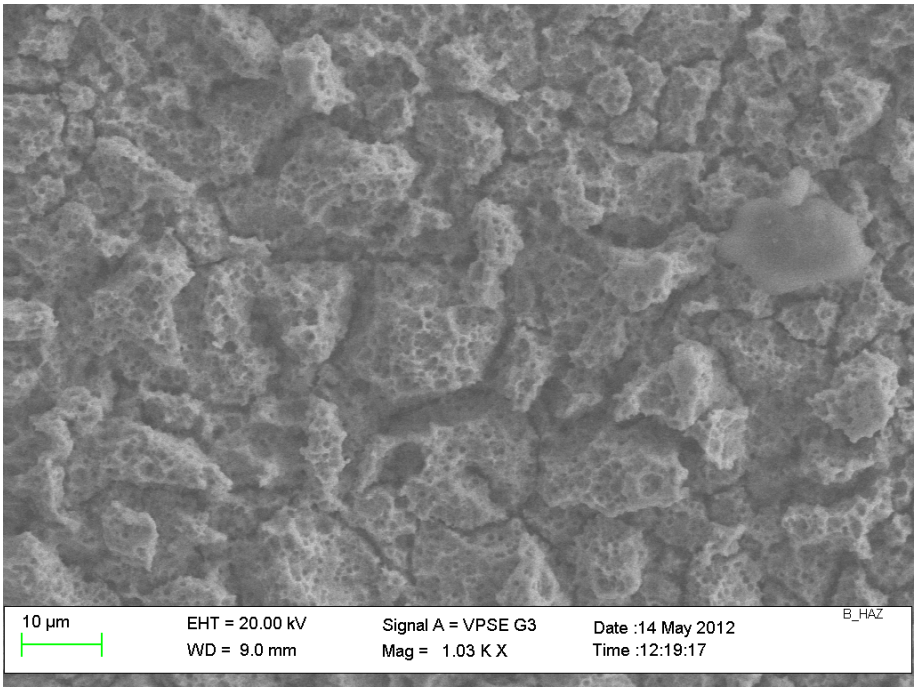


Plate 4.10: Micrograph of the Heat Affected Zone for Sample B

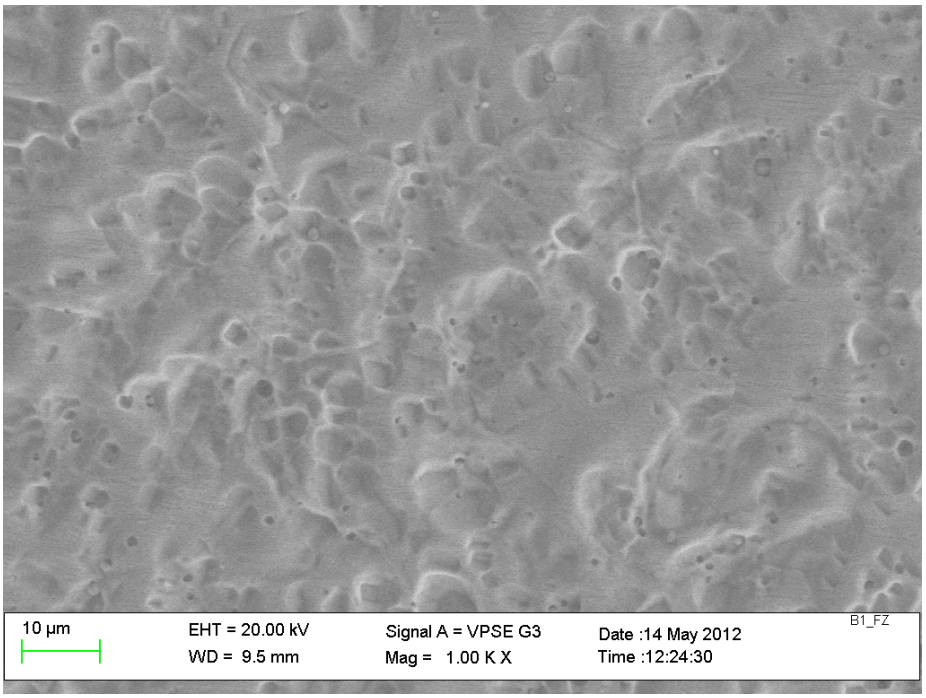


Plate 4.11: Micrograph of the Fusion Zone for Sample B1

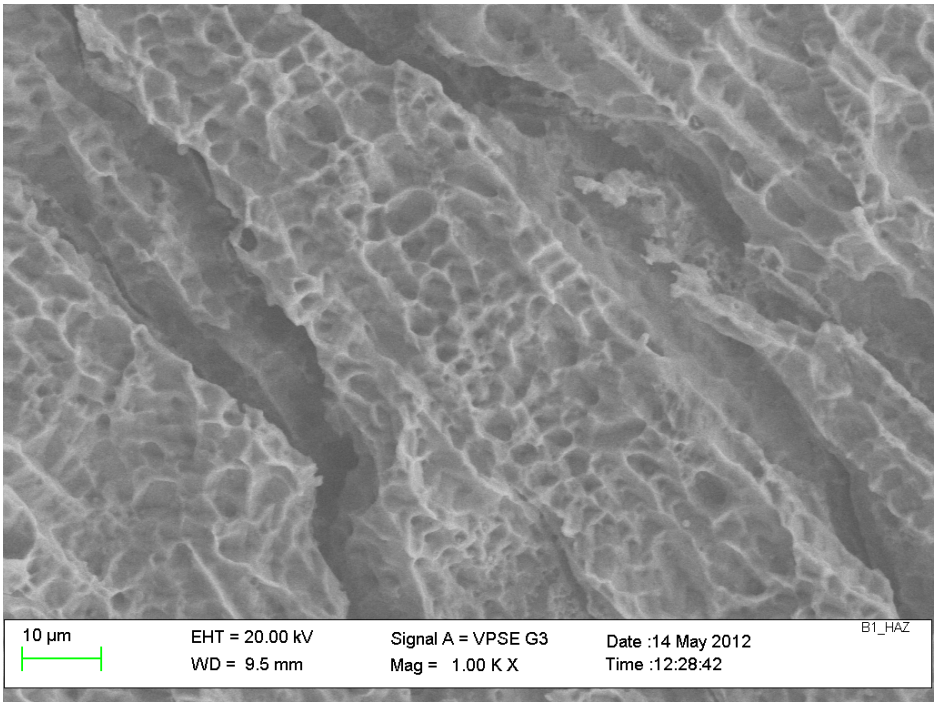


Plate 4.12: Micrograph of the Heat Affected Zone for Sample B1

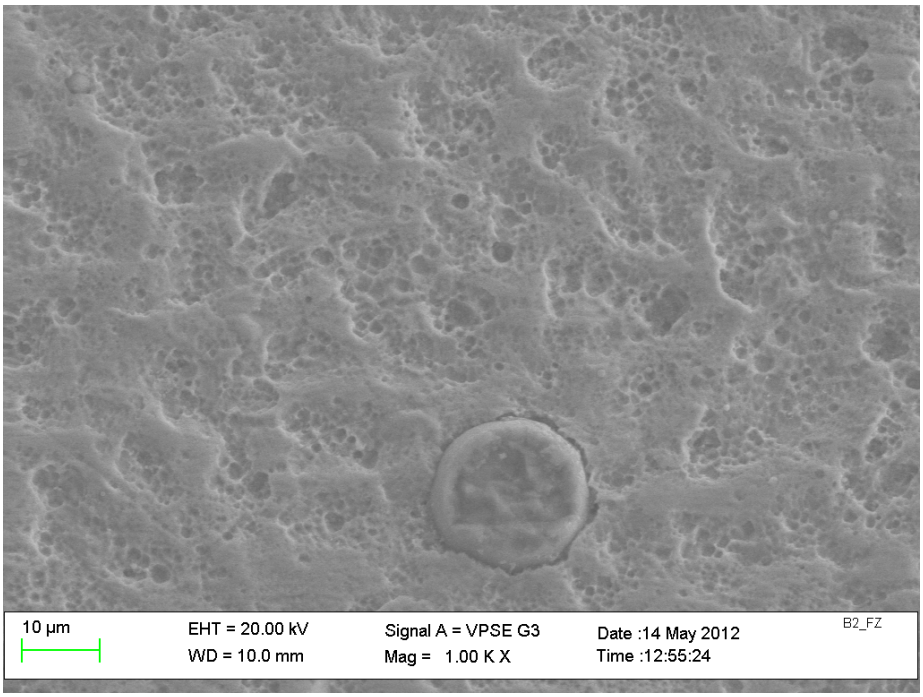


Plate 4.13: Micrograph of the Fusion Zone for Sample B2

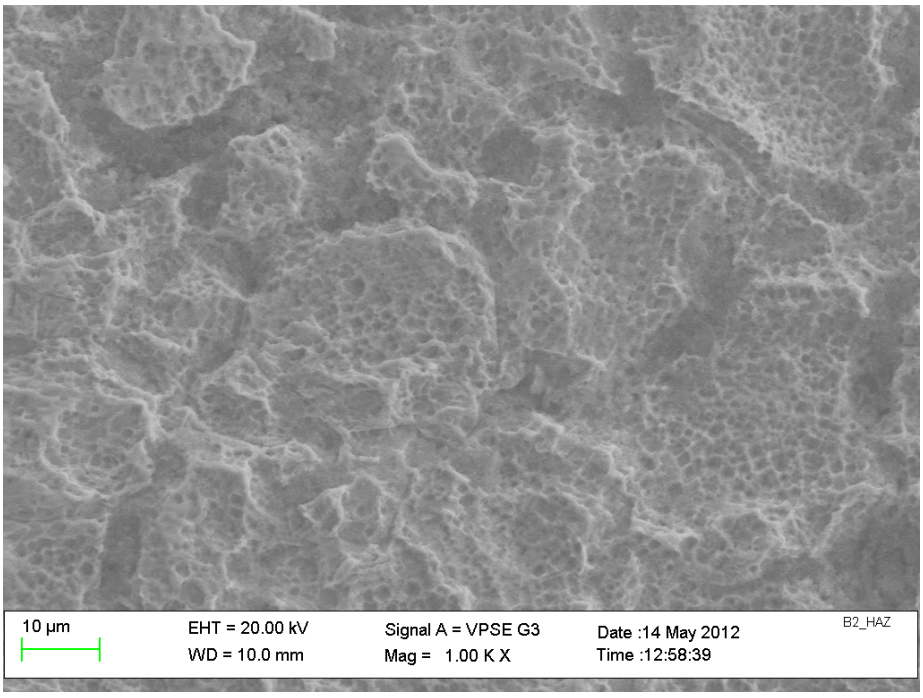


Plate 4.14: Micrograph of the Heat Affected Zone for Sample B2

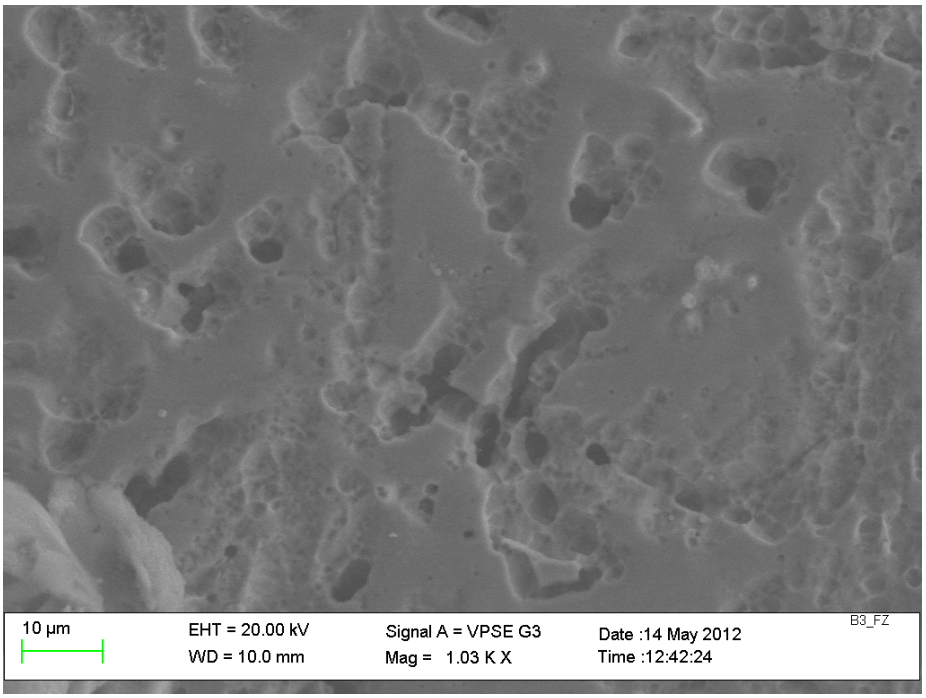


Plate 4.15: Micrograph of the Fusion Zone for Sample B3

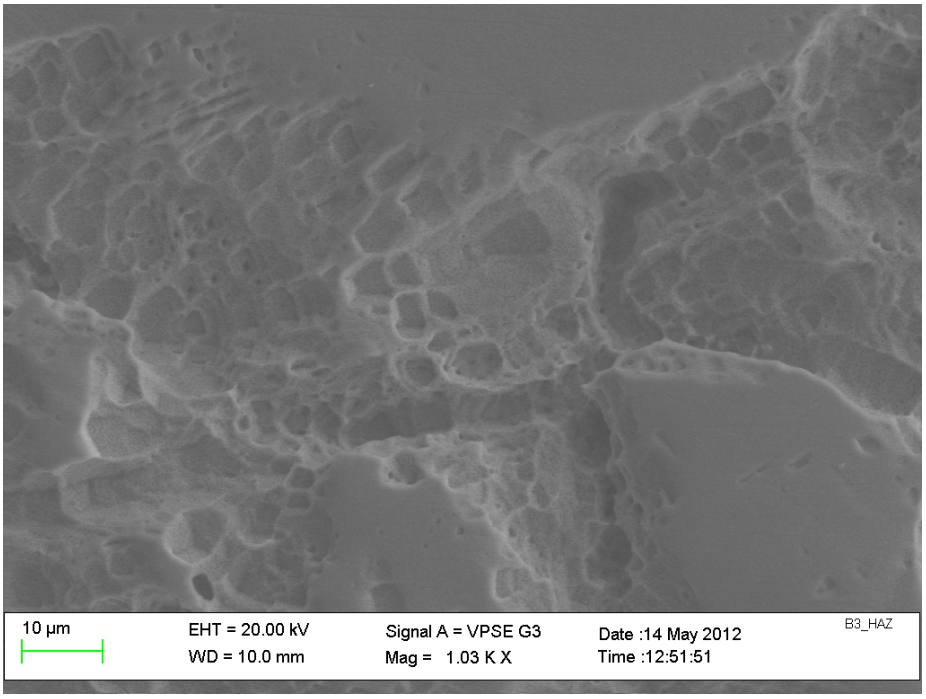


Plate 4.16: Micrograph of the Heat Affected Zone for Sample B3

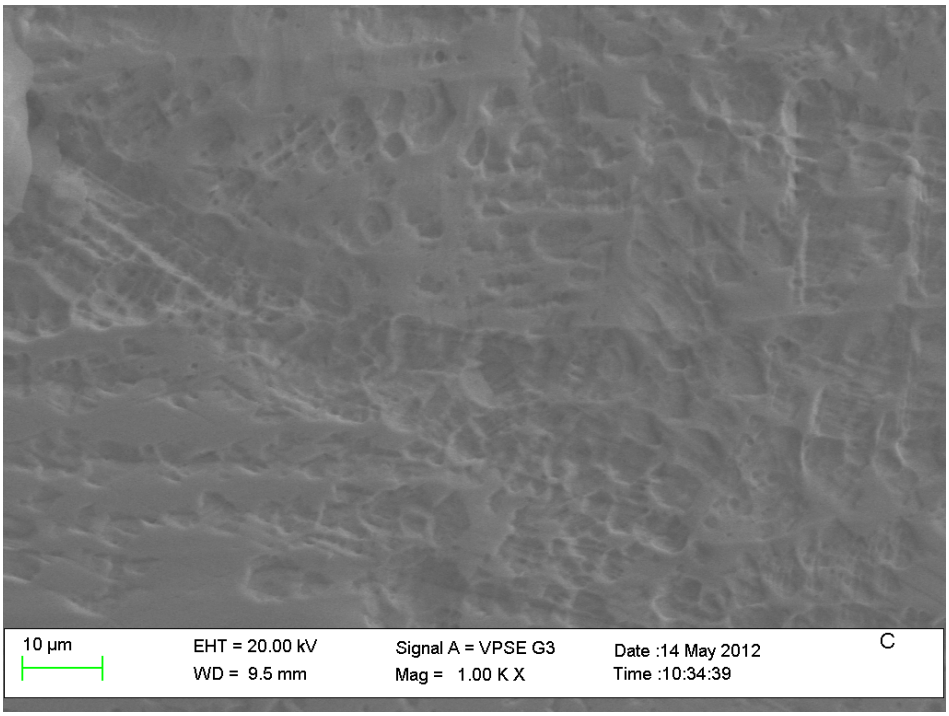


Plate 4.17: Micrograph for Sample C

4.1.3 MECHANICAL PROPERTIES OF THE SAMPLES

4.3.1 Tensile Properties of the samples

The results of the tensile tests carried out on the samples are recorded in table 4.2.

Table 4.2: The Tensile Tests Results for Samples

Area $A_0 = 7.85 \times 10^{-5}\ m^2$ **Gauge Length $l_0 = 50mm$**

Sample	Maximum Load (KN)	Tensile Strength (MN/m^2)	Extension (mm)	Elongation (%)
A	26.2	334	5.85	11.7
A_1	17.4	222	6.65	13.3
A_2	25.8	329	13.60	27.2
A_3	26.0	331	6.57	18
B	66.6	848	19.65	39.3
B_1	44.4	566	31.75	45.36
B_2	47.2	601	34.80	69.6
B_3	52.2	665	18.10	36.2
C	79.6	1010	35.00	70

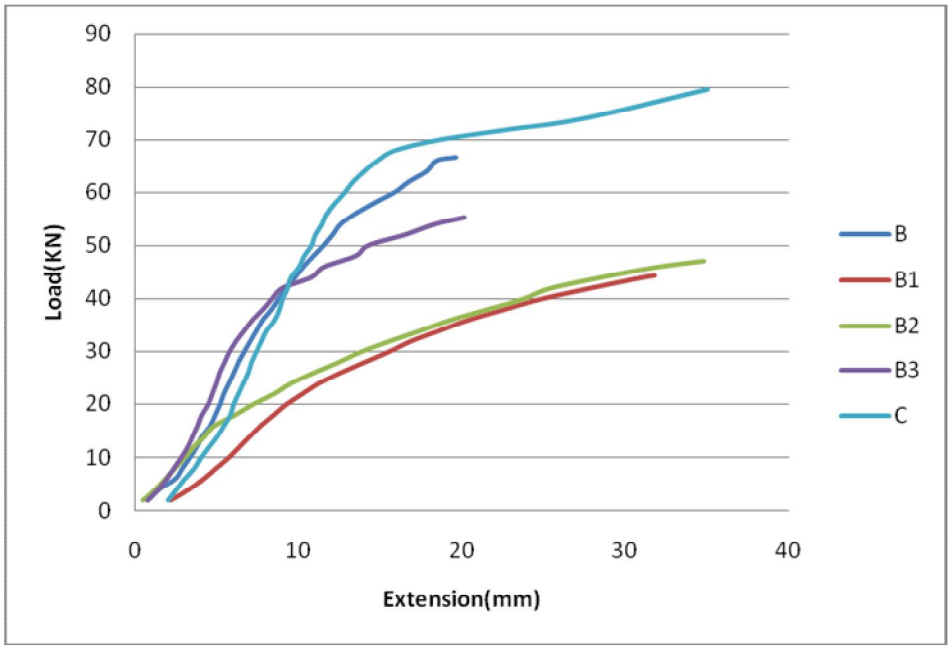


Fig. 4.1: Load vs Extension for Group B as compared to Control

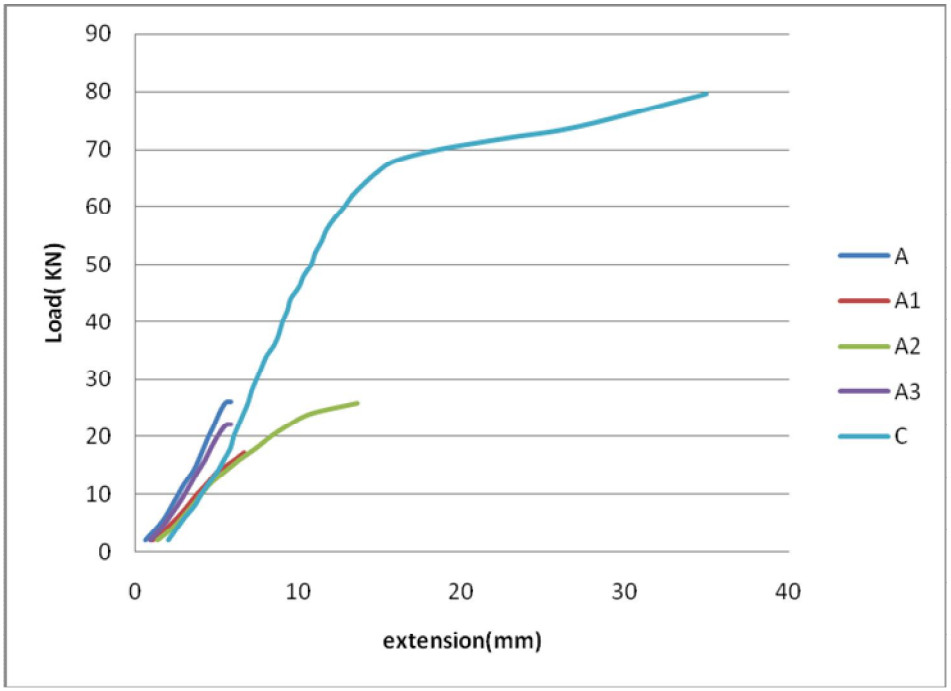


Fig. 4.2: Load vs Extension for Group A as compared to Control

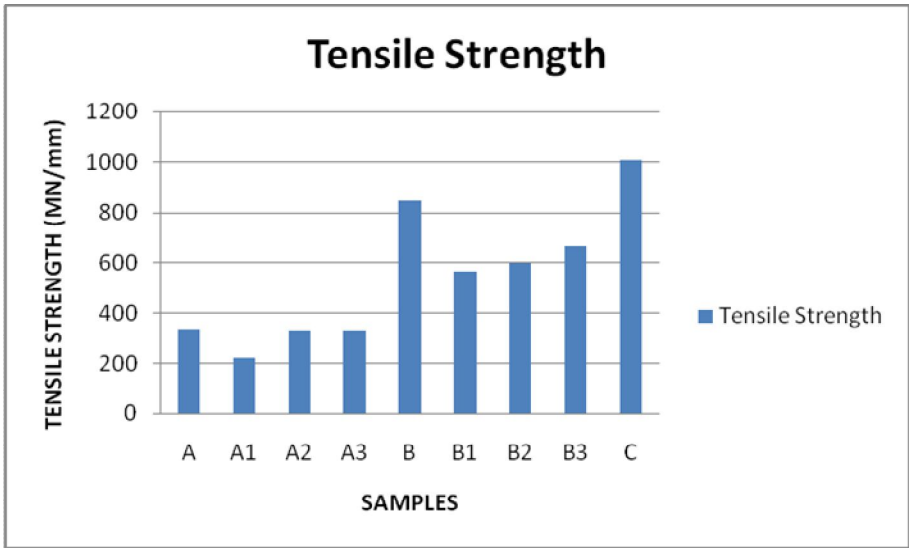


Fig. 4.3: Tensile Strength for Group A and Group B as compared to Control C

4.1.4 Impact Properties of the samples

The results of the impact test carried out on the samples are summarized in table 4.3.

Table 4.3: The Impact Tests Results for Samples

Sample	Average Energy (ft pound)	Average Energy Joules (J)
A	28.50	38.64
A_1	40.25	54.57
A_2	41.45	56.20
A_3	38.25	51.86
B	109.66	148.70
B_1	110.81	150.26
B_2	115.06	156.02
B_3	109.99	149.14
C	120.00	162.70

The comparison of the impact energy for group A samples with the as received one is shown in Fig. 4.6, while that of group B samples is on Fig. 4.7.

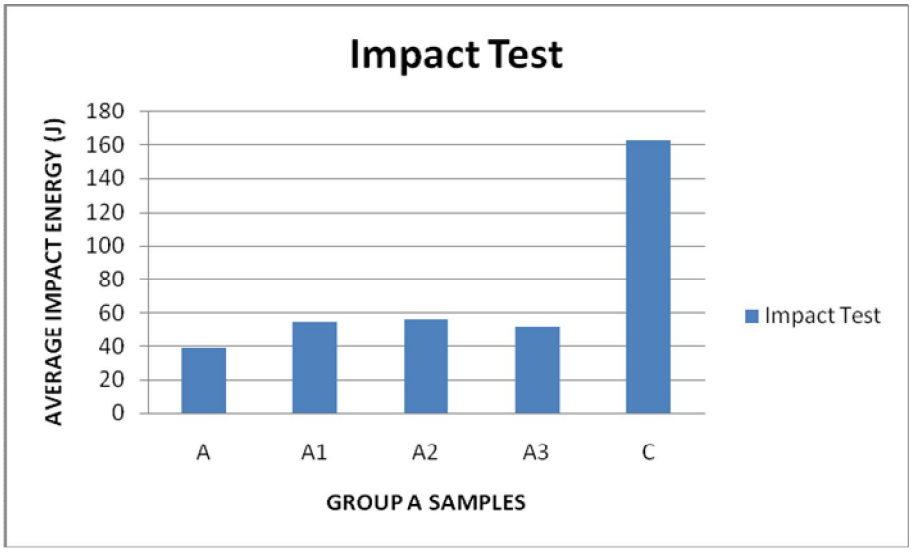


Fig. 4.6: Impact Energy for Group A as compared to Control

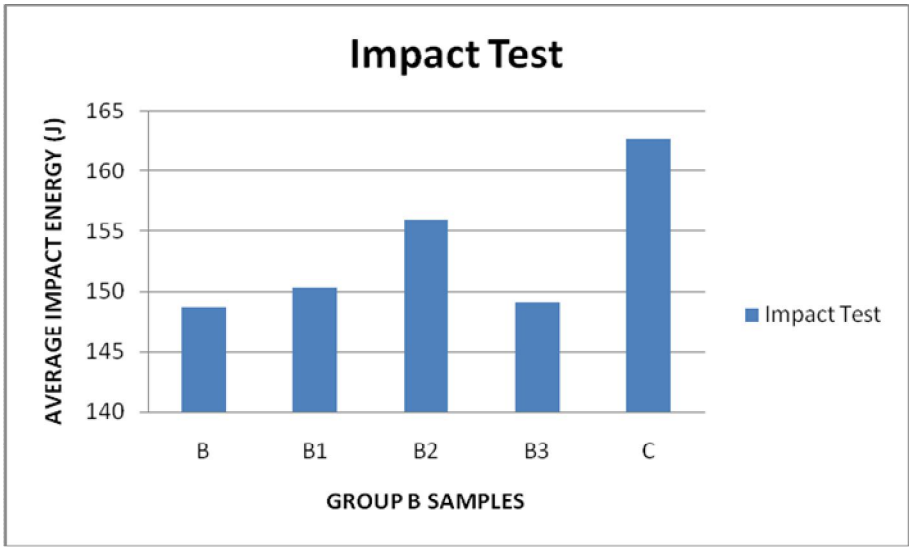


Fig. 4.7: Impact Energy for Group B as compared to Control

4.1.5 Hardness Number for the samples

The results of the hardness test carried out on the samples are summarized in table 4.4.

Table 4.4: Hardness Number for the samples

Sample	Hardness value (HRA) FZ	Hardness value (HRA) HAZ
A	49.9	63.1
A_1	46.0	56.3
A_2	44.4	56.2
A_3	49.5	60.3
B	52.3	61.3
B_1	50	58.2
B_2	46.9	58.3
B_3	51.3	58.9
C	65.8	

The comparison of the hardness number for group A samples with the as received one is shown in Fig. 4.8, while that of group B samples is on Fig. 4.9.

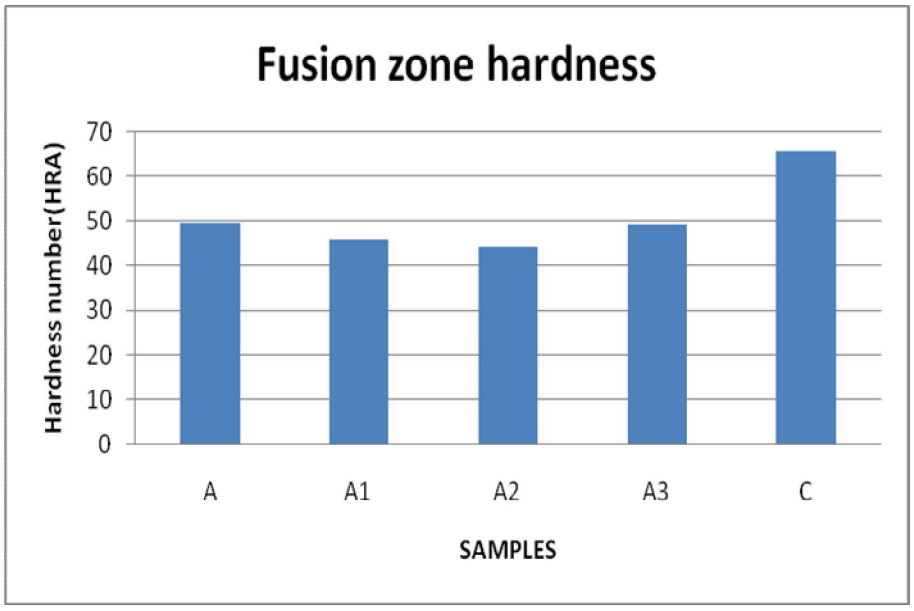


Fig. 4.8: Hardness Number for FZ of Group A as compared to Control

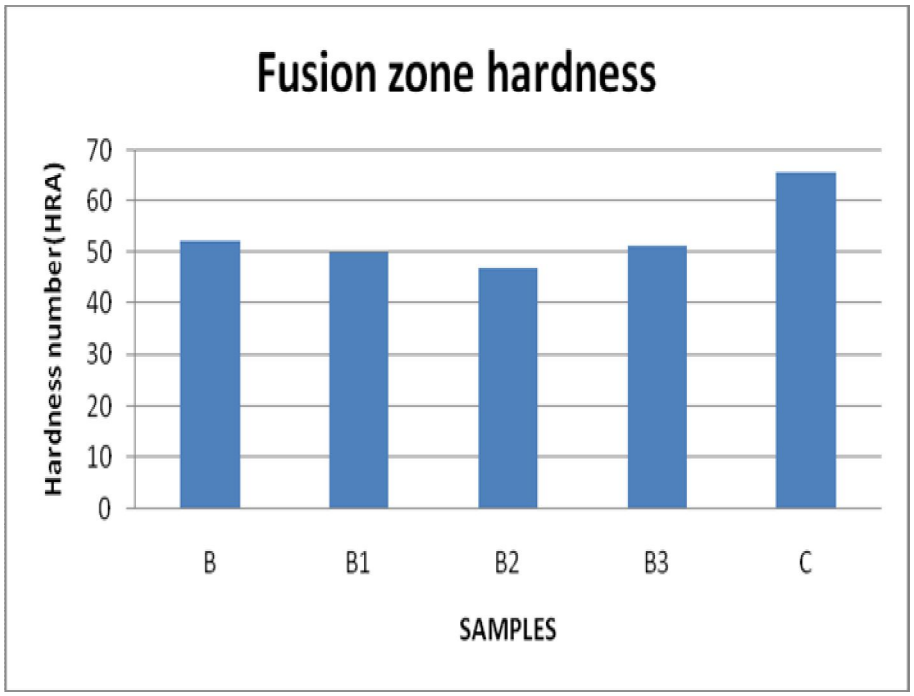


Fig. 4.9: Hardness Number for Group FZ of Group B as compared to Control

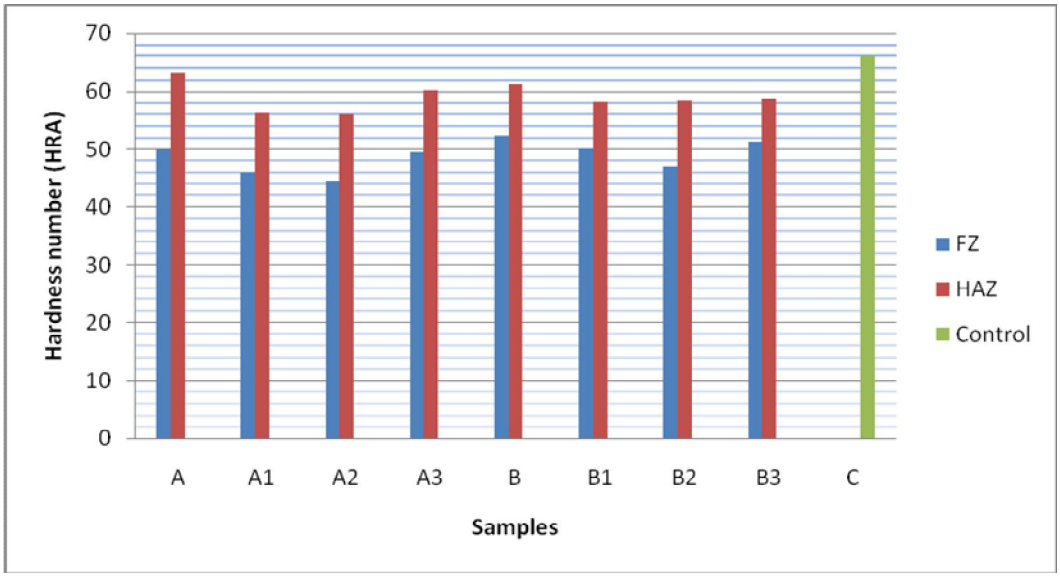


Fig. 4.10: Hardness Number for FZ and HAZ as compared to Control

4.2 Discussion

4.2.1 Scanning Electron Micrograph of Samples

SEM was used to study the morphology of all the welded and as received samples. Plate 4.17 shows the SEM micrograph of as received sample, Plate 4.1 to 4.8 shows the SEM micrographs of the group A samples, while Plates 4.9 to 4.16 show the SEM micrographs of the group B samples.

Morphological analysis using SEM clearly show difference in the morphology of the heat affected zone and the parts that are not affected, causing the grains of the heat affected zone to be more coarse than those of the unaffected zone (Plate 4.2). The microstructure clearly shows that there will be great influence of this change in morphology to the properties of the welded samples.

The microstructure of the as received sample shows a fine grain boundary and an indication of a better blending of the parent material and the alloying elements (Plates 4.17). From the SEM micrograph, there was great variation in morphology of the fusion zone and heat affected zone for each sample. This is due to the difference in the cooling rate of the two zones. (Compare Plate 4.1 and 2, 4.3 and 4 etc).

Finally, the grain sizes of the heat affected zone for samples A2 and B2 are shown to be finer as compared to other samples in the group. This is expected to give them better properties in their group. The basic information obtained from the SEM micrograph is in agreement with observations raised by other researchers (Rohatgi et al, 1988, Whitehouse et al, 1991, Zhou and Xu, 1997), while the relationship between the microstructure and the properties of the welded DSS agrees with conclusions of Pothan et al, (1997), Shangjin et al, (2001), Mohanty et al, (2002) and Madugu, et al (2010). These researchers showed that the grain size has a measurable effect on most of the mechanical properties such as hardness, yield strength, tensile strength, impact strength, these properties increases as the grain size decreases,

4.2.2 Tensile Properties of the sample

The results of the tensile tests carried out on the samples, as recorded in the table 4.2 and as shown in fig4.1 and fig 4.2 above showed that, carrying out post welding treatment increases the ductility of the samples, thereby making the materials to be tougher thus a decrease in their tensile strengths. The results also show that, quenching the samples in engine oil after welding highly increases their ductility, making them to have highest elongation. This can be associated to the fine grain size as revealed by the micrograph, compared to that of those samples in the groups (Plate 4.6 and 4.14). Fig. 4.1 and 4.2, this also showed that those samples that were not heat treated absorbed more load than those that were heat treated, and the reverse is the case of the extension.

The results also showed that heat treated samples that undergo stress relief treatment after welding posses better properties in terms of strength, next those that were treated in engine oil, followed by those treated in neem oil as shown in fig 4.3. The results obtained from the tensile test of the welded duplex stainless steel are in agreement with those obtained by other researchers [Donne et al (1990), Sagail and Leisk (1992), Asthana, (1998), Clyne, (2000) and Yetgin et al (2008)]. They show that the tensile strength increases as the grain size decreases and also tensile strength depends on the type of heat treatment carried out.

4.2.3 Impact Properties of the Sample

The results of the impact test carried out on the samples as recorded in Table 4.3 and as shown in Fig4.6 that the impact energy of the material rises from 38.64J obtained in the non treated sample A, to 56.2J obtained in sample A2, which is the highest for group A, then fall to 51.86J obtained in sample treated in neem oil. The same variation occurs in group B, as sample B2 has the highest impact energy of 156.02J. These variations can be related to the morphology of the microstructures, A2 and B2 have the finest microstructure in the HAZ in both groups.

Also, the results showed that samples that are welded using SMAW absorb more impact energy than those welded with GMAW which are treated the same way. This could be as a result of the fine microstructure observed in the samples welded with SMAW compared with the coarse microstructure in the GMAW process. The impact energy absorbed by Group B samples are close to that of the as received sample which absorbed 162.70J before it fails.

The variation in the impact strength is in agreement with variation of their elongation at failure during tensile and hardness tests carried. The result obtained from this test is in agreement with those obtained by these researchers, (Bonnefois et al, (1991), Uygur and Dogan(2005) and Gunn (1997)).

4.2.4 Hardness Properties of the sample

The results obtained from the hardness test showed that the hardness values of the treated samples differ from those obtained from samples that are not treated, depending on the kind of treatment carried out on them (Fig. 4.8 and 4.9).

The variation in the hardness values of the samples also agrees with observations made by Cottu et al, (1992) Mishra et al, (1999), Kock, (2000) and White et al, (1993). They showed that hardness is a function of grain size and the type of heat treatment carried out.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

From the analyses carried out on the samples and the discussions, following conclusions can be drawn:

i. The duplex stainless steel can be welded successfully using either shielded metal arc or gas metal arc welding process depending on the application or service life which the material will be subjected to.

ii. Both lubricating oil and neem oil can serve as quenching media for post weld treatment of duplex stainless steel.

iii. The shielded metal arc welding process gave the welded samples properties close to that of the un-welded sample (as received) compared to the gas metal arc welding method.

iv. Lubricating oil (85W90) serves as a better medium for treating the welded duplex stainless steel, as it is expected to increase its tensile strength, ductility and toughness.

v. Tempering after quenching improved the mechanical properties of the alloy.

vi. The tensile test, impact test and the hardness test show that welding has a negative effect on the mechanical properties of this alloy.

5.2 RECOMMENDATIONS

The following recommendations can also be made:

i. Research should be carried out on the corrosion aspects of this important alloy steel because during etching nine etchants (Nital, picral, kalling's No2, keller's, marble's reagent, kroll's reagent, viella's reagent etc) were not able to etched this alloy.

ii. Government should try and finance some of this research and provide equipments like other nation are doing.

iii. Research works should be carried out on the fracture toughness on this important alloy because of its exceptional mechanical properties.

REFERENCES

Afolabi, A.S (2007). Corrosion and Stress Corrosion Behaviors of Low and Medium Carbon Steel in Agro-field Media. Leonard Electronic Journal of Practices and Technologies, ISSN 1583-1078, Issue 10, Pp 55-66

Afolabi, A.S and Borode, J.O. (2007). Stress Corrosion Cracking Susceptibility of Medium Carbon Steel in Cautic and Potash Media. AU Journal of Technologies Pp 165-170

Asthana, R (1998): Solidification Processing of Reinforced Metals. *Transport Technology Publications;*Switzerland, 1998, Pp 421

Atamert, S.A.K., J.E. (1993). Sigma-Phase Formation and Its Prevention in Duplex Stainless Steels. Journal of Materials Science Letters, 12(14): Pp. 1144-1147

Balmforth.M .C , Lippold J.C (2000). A New Ferritic-Martensitic Stainless Steel Constitution Diagram. Welding Research Journal Pp 339-345.

Bhaduri, A.K., Albert, S. K., Ray, S.K. and Rodriguez (2003). Recent Trends in Repair and Refubishing of Steam Turbine Component. Sahdhana; 24(3&4), 395-408

Bonnefois B., Charles J., Dupoiron F. and Soulignac, P.(1991). How to Predict Welding Properties of Duplex Stainless Steels. In Duplex Stainless Steel 91.

Charles J (2011). Past, Present And Future of Duplex Stainless Steels Retrieved, 19th October, 2011 from www.arcelormittal.com

Charles J. (1991), Welds in Duplex Stainless Steels, Proc. Duplex Stainless Steels '91, Beaune, France, 151-168.

Charles, J.(1994) Structure and Mechanical Properties of Duplex Stainless Steels. Proc conf Duplex Stainless Steels '94, Glasgow, TWI, 1994, Vol.1, paper KI

Charles, J. (1995). Composition and Properties of Duplex Stainless Steels. Welding in the World, Vol. 36:Pp. 43-55.

Charles J (1997). Why and Where Duplex Stainless Steels. Duplex Stainless Steels '97 Maastricht, Netherlands 1 (1997) Pp29-42.

Claes-Ove. P, Sven-Áven .F (1995).Welding Practice for the Sandvik Duplex Stainless Steels SAF 2304, SAF2205 and SAF2507.

Clyne, T. W. (2000). Comprehensive Composite Materials. *Journal of Metal Matrix Composite*, 3:1-8

Cottu, J. P., Coudere, J. J., Viguier, B. and Bernard, L. (1992). *Journal of Material Science*, 27: 3068-3074

Dauda, E. T. (2008). Weldability Assessment of Some Locally Sourced Steels, Phd Dissertation Department of Metallurgical Engineering A. B. U Zaria.

Davison, R.M.R., J. D.,(1990). Practical Guide to Using Duplex Stainless Steels. Materials Performance, 1990. 29(1): Pp. 57-62.

Donne, S, Krishnadev, M.R and Bouchard, R (1990): Metal and Ceramic Matrix Mechanical Behavior. *The Minerals, Metals and Materials Society,* vol. 42 243-251

Gooch, T.G (1991) Corrosion resistance of welds in duplex stainless steels, in duplex stainless steel 91.

Guha, P. Clark, C.A. (1984). Improvements on Corrosion Resistance, Mechanical Properties and Weldabilty of Duplex Stainless Steels. Proc. Duplex Stainless Steels '82, St Louis, MO, ASM, :355-369.

Gunn, R., (1997). Duplex Stainless Steels - Microstructure, Properties and Applications. 1997, Abington Publishing: Cambridge England.

Henrik, S., Sandtrom, R,.(2006). Fracture Toughness of Welded Duplex Stainless Steel. Engineering Fracture Mechanics, Vol 73, issue 4:377-390

Hertzman, S., Nilsson, J.-O., Jargelius-Pettersson, R., Huhtala, T., Karlsson, L., Nilsson, M. and Wilson A. (1997). Microstructure Properties Relationship of Mo andW-alloyed Superduplex Stainless Steels. Mater. Sci. Tech. 13 :604-613.

Holmberg, B. (1994). Filler Material Selection for Optimum Duplex Weldment Properties in Steel UNS 31803. in Duplex Stainless Steels 94.

Jargelius-Pettersson R.F.A. (1999), Electrochemical Investigation of the Influence of Nitrogen Alloying on Pitting Corrosion of Austenitic Stainless Steels Corros. Sci. 8:1639-1664.

Jargelius-Pettersson, R.F.A. Flyg, J. and Wessman S. (1999), The Influence of Nitrogen Alloying on the Pitting and Crevice Corrosion of Austenitic and Duplex Stainless Steels Materi. Sci. Forum :318-320 :489-494.

Jerzy, L.and kyrzysztof. K (2005). The Influence of Welding Thermal Cycles on Corrosion Resistance of Duplex Stainless Steel. Advanced Materials Science, Vol. 5 NO. 2(7) June Pp 55-61.

Jonathan. B, and Gordon. J (1999). Introduction to Stainless Steels 3rd Edition. ASM International.

Kock,J .W (2000). Physical and Mechanical Properties of Chicken Feather Materials. Msc Thesis Presented to the Academic Faculty Georgia Institute of Technology.

Kokawa, H., Tsory, E. and North, T.H (1995). Nitride Precipitation in Duplex Stainless Steel. Steel Weld Metal. ISIJ International 95 8(10): p1277-1283

Kuroda, T.A.M., (1994). Role of Secondary Austenite on Corrosion and Stress Corrosion Cracking of Sensitized Duplex Stainless Steel Weldments, in Transactions of JWRI. 1994. Pp. 205-211.

Labanowski, J.(2007) Mechanical Properties and Corrosion Resistance of Dissimilar Stainless Steel Welds, Arhives of Material Science and Engineering vol 28 no.1 pp27-33

Labanowski, J .and Krzysztofowicz,K. (2005) , the Influence of Welding Thermal Cycles on Corrosion Resistance of Duplex Stainless Steel.
www.pg.gda.pl/mech/kim/ams/022005/ams02200503.pdf

Lardon, J.M., Charles, J., Dupoiron, F.and Bavay J.C. (1989), Microstructure and Properties of Welds in the Lean Duplex Stainless, Proc. HNS '88, Lille, France, :280-287.

Liljas, M. and Qvarfort R. (1986),Microstructure and Properties of Welds in the Lean Duplex Stainless steel, Proc. Duplex Stainless Steels '86, The Hague, NL, NIL (1986) 244-256/acom :1-2 2-12.

Liljas, M. (1994). The Welding Metallurgy of Duplex Stainless Steels. In Duplex Steels 94.

Liljas M. (1995), Proc. Duplex Stainless Steels '94, Glasgow, Scotland, Paper KV, 2 15pp.

Madugu, I. A, Abdulwahab, M. and Aigbodion, V.S. (2010). Effect of Iron Filings on the Properties and Microstructure of Cast Fibre-Polyester/Iron Filings Particulate Composite. Journal of Alloys and Compounds, :808-811.

Metrode, Metrode Welding Consumables - Technical Handbook. Retrieved, 19th January, 2012 from www.**metrode**.com/en-gb/profile/**technical**-support.html

Mishra S. C., Nayak. N.B and Satapathy,a. (1999). Investigation on Bio-waste Reinforced Epoxy Composites, *Metallurgical and Materials Engineering Department, National Institute of Technology, Rourkela, India*. Pp 119-123.

Miura, M., Koso, M., Kudo, T.and Tsuge, H. (1990) The Effects of Nickel And Nitrogen on the Microstructure and Corrosion Resistance of Duplex Stainless Steel Weldments, Welding International.4 (3):200-206.

Mohanty A.K., Misra M., and Drzal L.T., (2002). Sustainable Bio-composites from Renewable Resources: Opportunity and Challenges in the Green Materials World. Journal of Polymer nad Environment; 10:19–26

Nilsson, J. O. (1992). Super Duplex Stainless Steels, Material Science Technology, 8 (1992) Pp 685-700.

Nowacki .J, and Rybicki,P. (2007). Corrosion Resistance of SAW Duplex Joints Welded with High Heat Input. Journal of Achievements in Materials and Manufacturing Engineering Vol. 23 Issue 2 august 2007 Pp 7-14.

Ogawa, T. and Koseki T. (1989). Behavior Of Duplex Stainless Steel Weld Metals, Welding Journal, V68 N5, pp 181-s to 191- s.

Olsson, C.O., and A. Landolt D. (2003), Passive Films on Stainless Steels--Chemistry, Structure and Growth, Electrochim. Acta 48 (9):1093-1104.

Outokumpu Corrosion Handbook (2009), Tenth Edition, Sandvikens Tryckeri.

Parmer, R.S (2004). Welding engineering and technology, 1st edition 3rd reprint Khnanna publishers. 2B. Nath Market, Nai Sarak Delhi-10006- India. Pp 9-60, 188-206, 500-579 and 882.

Pascoe K.J (1982). An Introduction to the Properties of Engineering Materials English Language Book Society and Van Nostrand Reinhold (UK) Co. Ltd Pp114-116.

Pierre, J.C (2007). Welding of Stainless Steels, Material and Application Series, vol 3. Retrieved, 24th October, 2011 from www.euro-inox.org/htm/p_1_EN.html

Pothan L. A, Thomas S and Neelakantan, (1997). Short Banana Fiber Reinforced Polyester Composites: Mechanical, Failure and Aging Characteristics, *Journal of Reinforced Plastics and Composites*, 16(8): 744-765.

Praxair: Gas Metal Arc Welding of Stainless Steels. Retrieved, 19th October, 2011 from www.**praxair**.com/**praxair**.nsf/0/.../$FILE/P-8126.pdf.htm

Rohatgi P.K., Yarandi, F.M and Liu, Y. (1988). Segregation of SiC, Proc. of Inter. Symposium on Advances in Cast Reinforced Metal Composites (S.G. Fishman and A.K. Dhingra, eds.), *Materials Park, OH: ASM International Publication*: 249

Roscoe, C.V.and Gradwell K.J. (1986), The history and development of duplex Proc. Duplex Stainless Steels '86, The Hague, NL, NIL :126-135.

Sagail, A.,and Leisk, G. (1992): Heat Treatment Optimization of Alumina/Aluminium Metal Matrix Composites Using the Taguchi Approach. *Journal of Scripta Metallurgica et Material:* 871-876

Sakai, J., Matsushima, I., Kamemura, Y., Tanimura, M. and Osuka T. (1984), "Effects of Metallurgical Factors on Service Performance of Duplex Stainless, Proc. Duplex Stainless Steels '82, StLouis, MO, ASM : 211-231.

Sandvik Stainless Steels (2001), Your Guide to Easy Welding of Duplex Stainless Steel. Retrieved, 17th October, 2011 from www.steel.sandvik.com.

Shangjin H., Keyu, S., Jie, B., Zengkun, Z., Liang, L., Zongjie, D., and Baolong, Z. (2001). Studies on the Properties of Epoxy Resins Modified with Chain-Extended Ureas, *Journal of Polymer,* 42: 9641–9647.

Sieurin, H. and Sandstrom,R.(2006). Modeling Solid Solution Hardening in Stainless Steels, Materials Science Eng. A 415 Pp66-71.

Solomon, H.D. and Devine T.M. (1984), A Tale of Two Phases, Proc. Duplex Stainless Steels '82, St Louis, MO, ASM :693-756.

Sridhar, N.and Kolts J. (1987), Effects of Nitrogen on the Selective Dissolution of a Duplex Stainless Steel, Corrosion, Vol 43 (No. 11), 1987, p 646-651. 29.

Stainless Steels (2011). Duplex Stainless Steel Welding, Best Practices. Retrieved, 19th October, 2011 from www.stainless steels.net

Taylor, R (1994). Duplex Stainless Steel Production. in SFSA T&O conference.

Truman, J.E. Coleman, M.J. and Pirt, K.R. (1977), Influence of Nitrogen Content on the Resistance to Pitting Corrosion of Stainless Steels, Brit. Corros. J. 12 4 :236-238.

Tsuge, H. Tarutani, Y. and Kudo T. (1988), The Effect Of Nitrogen On The Localized Corrosion, Corrosion 44 :5 305-314.

Uygur,I. and Dogan,I.(2005) The effect of TIG Welding on Microstructure and Mechanical Properties of a Butt Joint Unalloyed Titanium, METALURGIJA 44 (2) 119-123

Vannevik, H., Nilsson, J.-O., Frodigh, J. and Kangas, P.,(1996). Effect of Elemental Partitioning on Pitting Resistance of High Nitrogen Duplex Stainless Steels. ISIJ International, 1996. 36(7):807-812.

Varol, I. Baeslack, III . W.A. and Lippold J.C. (1992), A Study of HAZ Liquation Cracking in. Duplex Stainless Steels, Key Eng. Mater. 69-70 :217-251.

Wallén, B., Liljas, M., Stenvall, P. (1992). A New High Molybdenum, High-Nitrogen Stainless Steel. Material Design 13 6 :329-333.

Wegrelius L. (1995), Passivation of austenitic stainless steel, Phd Dissertation, CTH, Gothenburg, Sweden.

Welding Engineer (2011). Duplex Stainless Steels Welding, Retrieved, 19th October, 2011 from www.**weldingengineer**.com/**Stainless**%20**Steel**.htm

Welding Expert(2011). Retrieved, 25th October, 2011 from www.**lincolnelectric**.com/en-us/support/Pages/resources.aspx

White, N.M .and Ansell, M.P. (1993). Straw Reinforced Polyester Composites. Journal of Material Science, 18:1549–56.

Whitehouse, A. F, Shahani, R. A. and Clyne, T. W. (1991). Metal Matrix Composites: Processing, Microstructure and Properties, 12 Risθ Int. Symp., Roskilde, N.Hansen et al., eds, Risθ National Laboratory, Denmark: 741-748

Yetgin. S., Cavdar, O.and Cavdar, A. (2008). The Effects of the Fibre Contents on the Mechanical Properties of the Adobes. Journal of Construction and Building Materials, 22: 222–227.

Zhou, W. and Xu, Z.M. (1997): Casting of SiC Reinforced Metal Matrix, *Journal of Material*s Processing Technology 63: 358-363

Appendix A

Table A1: The Tensile Test Result for Sample A

Load (KN)	Extension (mm)
2	0.6
4	1.25
6	1.8
8	2.2
10	2.6
12	3
14	3.5
16	3.85
18	4.15
20	4.45
22	4.8
24	5.1
26	5.5
26.2	5.85

Table A2: The Tensile Test Result for Sample A1

Load (KN)	Extension (mm)
2.0	1.10
4.0	1.90
6.0	2.60
8.0	3.20
10.0	3.75
12.0	4.40
14.0	5.00
16.0	6.00
17.4	6.65

Table A3: The Tensile Test Result for Sample A2

Load (KN)	Extension (mm)
2.0	1.37
4.0	2.25
6.0	2.90
8.0	3.50
10.0	4.05
12.0	4.65
14.0	5.27
16.0	6.37
18.0	7.40
20.0	8.30
22.0	9.50
24.0	10.60
25.80	13.60

Table A4: The Tensile Test Result for Sample A3

Load (KN)	Extension (mm)
2.0	0.9
4.0	1.55
6.0	2.05
8.0	2.55
10.0	3
12.0	3.4
14.0	3.8
16.0	4.25
18.0	4.6
20	5
22.0	5.5
22.2	5.85

Table A5: The Tensile Test Result for Sample B

Load (KN)	Extension (mm)
2.0	0.80
4.0	1.45
6.0	2.47
8.0	2.92
10.0	3.37
12.0	3.37
14.0	4.12
16.0	4.62
18.0	4.92
20.0	5.22
22.0	5.45
24.0	5.77
26.0	6.07
28.0	6.35
30.0	6.70
32.0	7.07
34.0	7.45
36.0	7.82
38.0	8.37
40.0	8.80
42.0	9.25
44.0	9.28
46.0	10.30
48.0	10.92
50.0	11.55
52.0	12.10
54.0	12.59
56.0	13.35
58.0	14.65

60.0	16.25
62.0	16.79
64.0	17.90
66.0	16.47
66.6	19.65

Table A6: The Tensile Test Result for Sample B1

Load (KN)	Extension (mm)
2	2.15
4	3.25
6	4.15
8	4.92
10	5.7
12	6.35
14	7
16	7.65
18	8.45
20	9.22
22	10.22
24	11.24
26	12.55
28	14.02
30	15.5
32	16.85
34	18.57
36	20.32
38	22.53
40	24.85
42	27.8
44	30.95

44.4	31.75

ble A7: The Tensile Test Result for Sample B2

Load (KN)	Extension (mm)
2.0	0.50
4.0	1.25
6.0	1.85
8.0	2.45
10.0	3.05
12.0	3.60
14.0	4.25
16.0	4.85
18.0	5.70
20.0	7.50
22.0	8.50
24.0	9.55
26.0	10.93
28.0	12.44
30.0	13.82
32.0	15.53
34.0	17.40
36.0	19.22
38.0	21.45
40.0	23.70
42.0	25.35
44.0	28.33
46.0	31.78
47.2	34.80

Table A8: The Tensile Test Result for Sample B3

Load	Extension

(KN)	(mm)
2.0	0.75
4.0	1.40
6.0	1.90
8.0	2.35
10.0	2.80
12.0	3.20
14.0	3.50
16.0	3.80
18.0	4.05
20.0	4.45
22.0	4.70
24.0	4.95
26.0	5.15
28.0	5.45
30.0	5.75
32.0	6.15
34.0	6.65
36.0	7.15
38.0	7.80
40.0	8.35
42.0	9.00
44.0	10.75
46.0	11.55
48	13.45
50	14.25
52	16.50
54	18.35
55.2	20.10

Table A9: The Tensile Test Result for Sample C

Load (KN)	Extension (mm)
2.0	0.80
4.0	1.50
6.0	3.00
8.0	3.60
10.0	4.00
12.0	4.50
14.0	5.00
16.0	5.40
18.0	5.80
20.0	6.00
22.0	6.30
24.0	6.60
26.0	6.90
28.0	7.10
30.0	7.40
32.0	7.70
34.0	8.00
36.0	8.50
38.0	8.80
40.0	9.00
42.0	9.30
44.0	9.50
46.0	10.00
48.0	10.30
50.0	10.76
52.0	11.00
54.0	11.40
56.0	11.70
58.0	12.20
60.0	12.80

62.0	13.30
64.0	14.00
66.0	14.80
68.0	15.90
70.0	18.60
72.0	22.90
74.0	27.30
79.6	35.00