COPYRIGHT AND CITATION CONSIDERATIONS FOR THIS THESIS/ DISSERTATION

○ Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made. You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.

○ NonCommercial — You may not use the material for commercial purposes.

○ ShareAlike — If you remix, transform, or build upon the material, you must distribute your contributions under the same license as the original.

How to cite this thesis
DETERMINING THE OPTIMUM WELDING MATERIAL OF 3CR12 STAINLESS STEEL

RESEARCH PROPOSAL

RAMAISELE MAPULE CONSTANCE MOLABE

Submitted to

The Faculty of Engineering and the Built Environment

For the degree of

MASTER’S IN ENGINEERING

MECHANICAL ENGINEERING

at the

UNIVERSITY OF JOHANNESBURG

SUPERVISOR : PROF. ESTHER T. AKINLABI

CO – SUPERVISOR : DR DANIEL M. MADYIRA

DATE : 13 May 2018
Copyright Statement

All rights reserved. The copy of this dissertation has been supplied on the condition that anyone who consults it is understood to recognize that its copyright rests with the University of Johannesburg. No part of this publication may be reproduced, stored in, or introduced into a retrieval system, or transmitted, in any form or by any means (electronic, mechanical, photocopying, recording or otherwise), without the prior written permission of the copyright owner, unless correctly referenced.
Plagiarism Declaration

- I, Ramaisele Mapule Constance Molabe, hereby declare that this dissertation is wholly my own work; and it has not been submitted anywhere else for academic credit – either by me, or another person.

- I understand what plagiarism implies; and I declare that this mini-dissertation is my own work: all the ideas, words, phrases, arguments, graphics, figures, results and organization – except where reference is explicitly made to another person’s work.

- I understand further that any unethical academic behaviour, which includes plagiarism, is seen in a serious light by the University of Johannesburg; and is punishable by disciplinary action.

Signed........................................ Date .........
Abstract

This research study called for investigation on a filler metal, which would yield improved benefits, when welding 3CR12 stainless steel. The compared filler metals included AISI 308L, 309L and 316L. The study was performed by welding 2mm thick 3CR12 test plates – using the TIG welding process by testing of welded material’s behaviour by tensile testing, microstructural analysis, and hardness testing. The experimental set-up and procedure were based on the findings from previous studies and recommendations.

Defect-free welds were achieved on all the welded samples. The parent metal showed ferrite and pearlite microstructure; while the Heat Affected Zone (HAZ) contained coarse grains, as compared with Base Material (BM) and the fusion zone, it had more ferrite and less pearlite microstructure. The coarse grains were due to the higher heat input in this region. The fusion zone consisted of austenite, ferrite and martensite laths; this was probably due to the dissimilar weld joints of the austenitic filler metal and the ferritic base metal. The fracture of the tensile specimens was consistently located in the parent-metal zone, suggesting that the strength of the welded joint is greater than that of the parent metal.

The ultimate tensile strength of all the samples is above the minimum (450MPa) ultimate tensile strength of the 3CR12. Owing to their fine grains at the weld joint, the welded joints displayed a higher tensile strength than that of the parent metal.

The microstructural analysis indicated that the 309L sample has larger grains on the HAZ than on the PM and fusion zone; this implies that the 309L is more susceptible to heat in the HAZ when compared with the 308L and 316L samples. The maximum hardness was found to be in the fusion zone in all the welded samples; as a result of the fine solidification structure. The hardness values for 309L samples are lower than those of 308L and 316L samples. The root of the weld was weaker than the weld cap for all the filler metals tested. Filler metal 308L was found to be the optimum welding material for 3CR12; and it can be recommended for producing welds with high quality and strong integrity.
**Glossary of Terms**

**A**

Electric arc – an electrical breakdown of gas that produces an ongoing electrical discharge.

Austenite – a solid solution of carbon in a non-magnetic form of iron that is stable at high temperatures.

Alloy – a metallic substance comprised of at least two chemical elements.

**B**

Backing – a material placed at the root of a weld joint to support the molten weld metal.

Base metal (material) – the metal (material) to be welded.

Butt weld – a weld joint in which the parts that are nearly parallel – but they don’t overlap, are connected.

**C**

Cap – the last bead of a weld.

Characterization – the broad and general process by which material’s structure and properties are probed and measured.

Charpy Impact Test – a test that measures the energy absorbed by a standard notched specimen while breaking under an impact load. It was invented by Georges Augustin Albert Charpy.

Columnar grains – grains that are elongated in a particular direction.

**D**

Defect – a discontinuity, which by nature or accumulated effect, renders a product unable to meet the minimum applicable specifications.

Ductile – able to be deformed – without losing toughness

Duplex – microstructure of roughly 50% austenite and 50% ferrite.
E
Electrode – electrical conductor used to make contact with a non-metallic part of a circuit.
Etching – the process of using strong acid to cut into the unprotected parts of a metal surface to view the design of the metal.
Equiaxed grains – grains that have the same length in all the different directions

F
Ferrite – a pure iron, with a body-centred cubic crystal structure.
Fibrous – consisting of fibres.
Filler metal – the metal to be added in making a welded joint.
Formability – the ability of a metal to undergo plastic deformation, without being damaged.
Fusion – the melting together of filler metal and base metal, or of the base metal only, which results in coalescence.
Fusion zone – the zone in which the molten powder and the molten substrate mix, or blend together.

G
Gas Tungsten Arc Welding (GTAW) – an arc-welding process, which produces coalescence of metals by heating them with an arc between a tungsten electrode and the base metal.
Globular grains – these are spherical grains.
Gas Flow Rate – the rate at which the gas is delivered onto a deposition platform.

H
Heat Affected Zone – the area of the base metal, which has not been melted, but whose mechanical properties or microstructure have been already altered by the heat of welding.

I
Indentation – the depression on the exterior surface of the metal.
Intergranular – situated or occurring between the grains.

J

Joint – the junction of members which have been joined together.

L

Laser – a device that generates an intense beam of coherent monochromatic light (or other electromagnetic radiation) by the stimulated emission of photons from excited atoms or molecules.

Laser Power – the amount of energy contained in or delivered by the laser beam.

Laths – thin plate-shaped.

M

Machinability – the degree or ease with which a material can be machined to an acceptable surface finish.

Martensite – a body-centred tetragonal form of iron, in which some carbon is dissolved.

Matrix – the crystalline phase in an alloy in which other phases are embedded.

Metallurgy – the extraction and processing of metals.

Microhardness – the surface hardness of a material measured on a small area.

Microstructure – the way in which the phases and defects in a material are arranged; and it is too fine; so that it can only be viewed by a microscope.

Molten-weld pool – the liquid state of a weld prior to solidification as a weld metal.

Morphology – study of the metal surface structure and shape.

O

Oxidizing – chemical combination with oxygen.

P

Parent metal (material) – the metal (material) to be welded.
Pearlite – a two-phased, layered or plate-like structure composed of alternating layers of ferrite and cementite.

Procedure qualification – the demonstration that welds made by a specific procedure can meet the prescribed standards.

R

Root of the weld – the point at which the back of the weld intersects the base-metal surface.

Resin – solid or highly viscous substance, which is typically convertible into polymers.

S

Solidification – the state at which molten metal begins to bond together and form a solid.

Sensitization – the precipitation of carbides at grain boundaries in an alloy, causing the alloy to be susceptible to intergranular corrosion or stress-corrosion cracking.

T

Transgranular – situated across the boundary between the grains.

W

Weldability – the ability with which a material can be welded

Welding procedure – the detailed methods and practices, including all joint welding procedures involved in the production of a weld.

Weld metal – that portion of a weld, which has been melted during welding.
# Table of Contents

Copyright Statement .................................................................................................................. ii
Plagiarism Declaration ................................................................................................................ iii
Abstract ...................................................................................................................................... iv
Glossary of Terms ....................................................................................................................... v
Table of Contents .................................................................................................................... 1
List of Figures ............................................................................................................................. 4
List of Tables ............................................................................................................................... 8
List of Symbols .......................................................................................................................... 9
Abbreviations ............................................................................................................................ 11

1 Introduction ................................................................................................................................. 13
   1.1 Introduction ......................................................................................................................... 13
   1.2 Problem Statement ............................................................................................................ 13
   1.3 Aim and Objectives ........................................................................................................... 13
   1.4 Hypotheses ......................................................................................................................... 14
   1.5 Methodology ....................................................................................................................... 14
   1.6 Significance of the Research ............................................................................................. 14
   1.7 Research Outline ............................................................................................................... 15

2 Literature Survey ..................................................................................................................... 16
   2.1 Introduction ......................................................................................................................... 16
   2.2 The Welding Process .......................................................................................................... 16
       2.2.1 Forge Welding ............................................................................................................. 16
       2.2.2 Fusion Welding .......................................................................................................... 16
   2.3 Arc Welding ........................................................................................................................ 17
       2.3.1 Welding Processes for Stainless Steel ......................................................................... 18
       2.3.2 Gas Tungsten-Arc Welding (GTAW) or Tungsten Inert gas (TIG) .............................. 22
   2.4 TIG wires ........................................................................................................................... 23
   2.5 Welding Parameters ........................................................................................................... 24
       2.5.1 Welding problems and defects: causes and remedies ............................................... 26
   2.6 Gas Tungsten-Arc Welding (GTAW) Joint Configurations ............................................. 31
   2.7 Stainless Steel .................................................................................................................. 32
       2.7.1 Weldability of Ferritic Stainless Steel ......................................................................... 32
       2.7.2 Heat Treatment .......................................................................................................... 34
List of Figures

Figure 2-1: Fusion Welding [50] ........................................................................................................... 17
Figure 2-2: Flux Cored-Arc Welding [16] .......................................................................................... 20
Figure 2-3: Submerged-Arc Welding [17] .......................................................................................... 20
Figure 2-4: Laser Welding [18] ......................................................................................................... 21
Figure 2-5: GTAW Welding, basic principle [49] ................................................................................. 22
Figure 2-6: GTAW Equipment Set up [5] ........................................................................................... 23
Figure 2-7: Spatter Defects [56] ........................................................................................................ 27
Figure 2-8: Deformation Defects [56] ............................................................................................... 27
Figure 2-9: Longitudinal Cracks in the HAZ Defects [56] ................................................................. 27
Figure 2-10: Arc-Striking Difficulties and Defects [55] ........................................................................ 28
Figure 2-11: Solidification Defects [56] ........................................................................................... 28
Figure 2-12: Lack-of-Fusion Defects [56] ......................................................................................... 29
Figure 2-13: Crater-Crack Defects [56] ............................................................................................ 29
Figure 2-14: Undercut Defects [56] .................................................................................................. 29
Figure 2-15: Porosity Defects [56] ..................................................................................................... 30
Figure 2-16: Slag Inclusion Defects [56] ............................................................................................ 30
Figure 2-17: Lack of Penetration Defects [56] ................................................................................... 30
Figure 2-18: Weld Positions and Joints for GTAW [49] .................................................................... 31
Figure 2-19: Stainless Steel Phases [21] .......................................................................................... 32
Figure 2-20: 3CR12 Categories [16] ................................................................................................ 35
Figure 2-21: Microstructure of fully ferritic, ultralow carbon steel. Marshalls etch + HF, 300x [51] ... 42
Figure 2-22: Iron-carbon phase diagram showing the austenite (\gamma\text{Fe}) and ferrite (\alpha\text{Fe}) phase regions and eutectoid composition and temperature. Dotted lines represent iron-graphite equilibrium conditions and the solid lines represent iron-cementite equilibrium conditions. Only the solid lines are important with respect to steels. [51] ........................................................................................................... 43
Figure 2-23: Microstructure of a typical fully pearlitic rail steel showing the characteristic fine pearlite interlamellar spacing. 2% nital + 4% picral etch. 500x. [51] ................................................................. 43
Figure 2-24: SEM micrograph of pearlite showing ferrite and cementite lamellae. 4% picral etch. 10000x. [51] ........................................................................................................................................ 44
Figure 2-25: Microstructure of typical ferrite-pearlite structural steels at two different carbon contents; 0.10%C and 0.25%C, respectively. 2% nital + 4% picral etch. 200x. [51] ................................................................. 44
Figure 2-26: Mechanical properties of ferrite-pearlite steels, as a function of carbon content [51] ... 45
Figure 2-27: Microstructure of (a) upper bainite and (b) lower bainite in Cr-Mo-V rotor steel. 2% nital + 4% picral etch. 500x. [51] ........................................................................................................................................ 46
Figure 2-28: Microstructure of a typical lath martensite and typical plate martensite, respectively. 4% picral + HCl. 200x. [51] ........................................................................................................................................ 46
Figure 2-29: Microstructure of fully spheroidized steel. 4% picral etch. 100x. [51] ............................... 47
Figure 2-30: Microstructure of typical dual-phased steel. 2% nital etch. 250x. [51] ............................... 48
Figure 2-31: Microstructure of a typical mill-annealed duplex stainless steel plate, showing elongated austenite islands in the ferrite matrix. Etched in 15mL HCL in 100mL ethyl alcohol. 200x. [51] ............................... 48
Figure 2-32: Classification of different graphite-flake morphologies. [51] ............................................ 49
Figure 2-33: Microstructure of a typical white cast iron. 4% picral etch. 100x. [51] ............................... 49
Figure 2-34: Microstructure of (a) As-received AISI 316, (b) As-received 3CR12, (c) Heat treated and water quenched AISI 316, (d) Heat treated and water quenched 3CR12, (e) Heat treated air cooled AISI 316 and (f) Heat treated air cooled 3CR12 ................................................................. 51
Figure 2-35: Vickers microhardness profile of AISI 316 as-received and heat treated samples ....... 52
Figure 2-36: Vickers microhardness profile of 3CR12 as-received and heat treated samples ........ 52
Figure 2-37: Microstructural morphologies of grains: (a) columnar grains in the fusion zone, (b) equiaxed grains in the fusion zone, and (c) base metal................................................................. 54
Figure 2-38: Micrographs of 12mm thick hybrid (PA+GTA) weld with 309 type of filler metal (I.9) (a) BM 200x, (b) root WM by PAW without filler metal 200x, (c) filler pass WM by GTAW with 309 type of filler metal 200x, (d) root HAZ 50x, (e) face HAZ 50x and (f) face HAZ 200x................................. 55
Figure 2-39: Micrographs of 12mm thick hybrid (PA+GTA) weld with 316 type of filler metal (I.6) (a) BM 200x, (b) root WM by PAW without filler metal 200x, (c) filler pass WM by GTAW with 316 type of filler metal 200x, (d) root HAZ 50x, root HAZ 50x and (f) face HAZ 200x................................. 56
Figure 2-40: HV5 graphs of (a) 309L filler metal (L9) and (b) 316LSi filler metal (L6)......................... 56
Figure 2-41: Micrographs of (a) hot rolled reinforcing bar material, (b) annealed 3CR12 steel, (c) cross section of the annealed and drawn 3CR12 steel wire and (d) quenched and drawn 3CR12 steel wire at cross section ................................................................. 58
Figure 2-42: Macrostructure of electron beam-welded 409M ferritic stainless steel: BM (a), fusion zone (b), HTHAZ (c) and LTHAZ (d) ................................................................. 61
Figure 2-43: Microstructure of electron beam welded 409M ferritic stainless steel joint ............ 61
Figure 2-44: Hardness profile of electron beam-welded 409M ferritic stainless steel joint ........ 62
Figure 2-45: (a) Austenite in 10%Cr10%Mn21% alloy annealed 1050 C and air cooled, and (b) surface martensite in an austenitic 12%Cr10%Mn32%N steel, annealed 1050 C and air cooled........ 63
Figure 2-46: (a) The microstructure of steel 3CR12 as cast, (b) Primary (P) and secondary (S) particles of Ti(C,N) in as cast steel 3CR12, (c) Islands of delta ferrite matric of austenite in as cast steel 304L. 64
Figure 2-47: The microstructure of steel (a) 3CR12 after hot rolling to 40% reduction, (b) 3CR12 hot rolled to 56% reduction and (c) 304 hot rolled to 29% ................................................................. 65
Figure 2-48: Optical micrographs of weld metals using 308L (a) and 316L (b) filler wires [42]....... 66
Figure 2-49: Microstructure of the welded joint for T4003 FSS, (a) weld zone, (b) base metal, (c)HAZ1, (d) HAZ2 and (e) HAZ3 ................................................................. 68
Figure 2-50: Microstructure and hardness value of the cross section of the welded joint .......... 68
Figure 2-51: Photomicrographs of GMA weld with 309 filler metal (B9). A—BM, 200x; B—WM+HAZ, 50x; C—HAZ, 200x; D—WM, 200x ................................................................. 70
Figure 2-52: Photomicrographs of GMA weld with 308 filler metal (B8). A—WM+HAZ, 50x; B— HTHAZ, 200x; C—HAZ, 200x; D—WM, 200x ................................................................. 70
Figure 2-53: Photomicrographs of GMA weld with 316 filler metal (B6). A—WM+HAZ, 50x; B—HAZ, 200x; LTHAZ, 200x; D—WM, 200x ................................................................. 71
Figure 3-1: 3CR12 Test sheet ........................................................................................................ 75
Figure 3-2: TIG welding Set-up ................................................................................................ 77
Figure 3-3: Welded Plates ........................................................................................................... 77
Figure 3-4: Welded Sample Lay-out ......................................................................................... 78
Figure 3-5: Tensile Test Sample ................................................................................................ 78
Figure 3-6: Cut-off Machine ...................................................................................................... 79
Figure 3-7: Hot Mounting Machine .......................................................................................... 80
Figure 3-8: Mounted Sample (Parent) ..................................................................................... 80
Figure A-12: Hardness Test Results at the Cap of the Weld (316L) ...........................................128
Figure A-13: Hardness Test Results at the Root of the Weld (308L, 309L, 316L & Parent) ..........128
Figure A-14: Hardness Test Results at the Cap of the Weld (308L, 309L, 316L & Parent) ..........129
List of Tables

Table 2-1: Guidelines for Selecting Welding Process for Stainless Steel [57] ................. 22
Table 2-2: Welding Parameters for Stainless Steel [14] .................................................. 24
Table 2-3: Typical TIG Welding Parameters [11] .......................................................... 25
Table 2-4: Edge Preparation for Stainless Steel [11] ...................................................... 26
Table 2-5: General Requirements for GTAW Welding of Stainless Steel [5] .................... 31
Table 2-6: Filler Metals for Stainless Steel Grades [21] ................................................... 33
Table 2-7: Compositional Development of 3CR12 [22] ............................................... 36
Table 2-8: Chemical Properties of 3CR12 [1] ............................................................... 37
Table 2-9: Mechanical Properties of 3CR12 [1] ............................................................ 37
Table 2-10: Creep Properties of 3CR12 [1] .................................................................. 37
Table 2-11: Physical Properties of 3CR12 [1] .............................................................. 38
Table 2-12: Mechanical Properties of Afrox’s 3CR12 Electrode [10] ............................. 39
Table 2-13: Mechanical Properties of Afrox’s 3CR12 Electrode [10] ......................... 40
Table 2-14: Chemical Properties of 309Mo-16 Electrode [4] ........................................ 41
Table 2-15: Mechanical Properties of 309Mo-16 electrode [4] .................................. 41
Table 2-16: Chemical Properties of 316 L-16 Electrodes [4] ....................................... 41
Table 2-17: Mechanical Properties of 316L-16 Electrodes [4] .................................... 42
Table 2-18: Mechanical properties of 3CR12 corrosion-resistant steel wire ............. 58
Table 2-19: Tensile and impact property of EBW joints in comparison with the base metal 62
Table 2-20: Mechanical properties .............................................................................. 63
Table 2-21: Data for steel 3CR12 ................................................................................. 65
Table 3-1: Experimental Matrix with 309L Filler Metal ............................................. 76
Table 3-2: Experimental Matrix with 308L Filler Metal ............................................. 76
Table 3-3: Experimental Matrix with 316L Filler Metal ............................................. 76
Table 3-4: Stainless Steel Cleaning Guidelines ............................................................ 81
Table 3-5: Stainless Steel Polishing Guideline [54] ..................................................... 82
Table 4-1: Microstructure Results (308L, 200µm) ....................................................... 88
Table 4-2: Microstructure Results (309L, 200µm) ....................................................... 89
Table 4-3: Microstructure Results (316L, 200µm) ....................................................... 90
Table 4-4: Microstructure Results for 308L, 309L & 316L Samples at 200µm .......... 91
Table 4-5: Microstructure at 200µm ......................................................................... 92
Table 4-6: Grain Size Summary ................................................................................. 94
Table A-1: Procedure Qualification Record (PQR) Page1 ........................................ 117
Table A-2: Procedure Qualification Record (PQR) Page2 ........................................ 118
Table A-3: Welding Procedure Specification (WPS) .................................................. 119
Table A-4: List of etchants and their chemical composition [53] ................................ 120
Table A-5: 3CR12 Chemical Composition .................................................................. 121
Table A-6: Costs for Filler Rods ............................................................................... 130
# List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>mm</td>
<td>Thickness</td>
</tr>
<tr>
<td>D, Ø</td>
<td>mm</td>
<td>Diameter</td>
</tr>
<tr>
<td>L</td>
<td>mm</td>
<td>Length</td>
</tr>
<tr>
<td>A</td>
<td>mm$^2$</td>
<td>Area</td>
</tr>
<tr>
<td>F</td>
<td>N/mm$^2$</td>
<td>Force</td>
</tr>
<tr>
<td>Δ</td>
<td>%</td>
<td>Elongation</td>
</tr>
<tr>
<td>ε</td>
<td>mm/mm</td>
<td>Strain</td>
</tr>
<tr>
<td>E</td>
<td>MPa</td>
<td>Elastic Modulus</td>
</tr>
<tr>
<td>σ</td>
<td>MPa</td>
<td>Stress</td>
</tr>
<tr>
<td>σ$_y$</td>
<td>MPa</td>
<td>Yield Strength</td>
</tr>
<tr>
<td>UTS</td>
<td>MPa</td>
<td>Ultimate Tensile Strength</td>
</tr>
<tr>
<td>W</td>
<td>kg</td>
<td>Weight</td>
</tr>
<tr>
<td>P</td>
<td>Kg/mm$^3$</td>
<td>Density</td>
</tr>
<tr>
<td>ρ</td>
<td>W/m.K</td>
<td>Conductivity</td>
</tr>
<tr>
<td>A</td>
<td>μm/m.K</td>
<td>Coefficient of thermal expansion</td>
</tr>
<tr>
<td>R</td>
<td>μm</td>
<td>Electrical resistivity</td>
</tr>
<tr>
<td>Ω</td>
<td>RPM</td>
<td>Rotational speed</td>
</tr>
<tr>
<td>V</td>
<td>ml</td>
<td>Volume</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>--------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>T</td>
<td>°C</td>
<td>Temperature</td>
</tr>
<tr>
<td>P</td>
<td>MPa</td>
<td>Pressure</td>
</tr>
<tr>
<td>V</td>
<td>V</td>
<td>Voltage</td>
</tr>
<tr>
<td>E</td>
<td>J</td>
<td>Energy</td>
</tr>
<tr>
<td>H_i</td>
<td>kJ/min</td>
<td>Heat Input</td>
</tr>
<tr>
<td>V_t</td>
<td>mm/min</td>
<td>Travel Speed</td>
</tr>
<tr>
<td>V_w</td>
<td>m/min</td>
<td>Wire Feed Speed</td>
</tr>
<tr>
<td>I</td>
<td>A</td>
<td>Current</td>
</tr>
<tr>
<td>Q</td>
<td>L/min</td>
<td>Flow rate</td>
</tr>
<tr>
<td>Θ</td>
<td>°</td>
<td>Electrode point angle</td>
</tr>
<tr>
<td>T</td>
<td>min</td>
<td>Time</td>
</tr>
<tr>
<td>HV</td>
<td>HV</td>
<td>Hardness</td>
</tr>
<tr>
<td>C</td>
<td>R</td>
<td>Cost (Rand)</td>
</tr>
</tbody>
</table>
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS&amp;A</td>
<td>Middelburg Steel and Alloys</td>
</tr>
<tr>
<td>SASSDA</td>
<td>South African Stainless Steel Development Association</td>
</tr>
<tr>
<td>HV</td>
<td>Vickers Hardness</td>
</tr>
<tr>
<td>AISI</td>
<td>American Iron and Steel Institute</td>
</tr>
<tr>
<td>BS</td>
<td>British Standard</td>
</tr>
<tr>
<td>UNS</td>
<td>Unified Numbering System</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>GTAW</td>
<td>Gas Tungsten Arc Welding</td>
</tr>
<tr>
<td>TIG</td>
<td>Tungsten Inert Gas</td>
</tr>
<tr>
<td>MIG</td>
<td>Metal Inert Gas</td>
</tr>
<tr>
<td>MMA</td>
<td>Manual Metal Arc</td>
</tr>
<tr>
<td>LSW</td>
<td>Laser Beam Weld</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>CFH</td>
<td>Cubic Feet per Hour</td>
</tr>
<tr>
<td>PSI</td>
<td>Pounds per Square Inch</td>
</tr>
<tr>
<td>In</td>
<td>Inches</td>
</tr>
<tr>
<td>Ipm</td>
<td>Inches per Minute</td>
</tr>
<tr>
<td>Amp</td>
<td>Ampere</td>
</tr>
<tr>
<td>Ni</td>
<td>Nickel</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>Ti</td>
<td>Titanium</td>
</tr>
<tr>
<td>Cr</td>
<td>Chromium</td>
</tr>
<tr>
<td>C</td>
<td>Carbon</td>
</tr>
<tr>
<td>Mn</td>
<td>Manganese</td>
</tr>
</tbody>
</table>
Fe  Iron
Nb  Niobium
MPa Mega Pascals
HAZ  Heat Affected Zone
HTHAZ High Temperature Heat Affected Zone
LTHAZ Low Temperature Heat Affected Zone
CET Columnar to Equiaxed Transition
DBTT Ductile-to-Brittle Transition Temperature
LSM Laser Surface Melting
EDS Energy Dispersive Spectroscopy
AES Auger Electron Spectroscopy
MC Metal and Carbon atom
PQR Procedure Qualification Record
WPS Welding Procedure Specification
PM Parent Metal
BM Base Metal
FZ Fusion Zone
HAZ Heat-Affected Zone
MIN Minimum
MAX Maximum
S Sample
UTS Ultimate Tensile Strength
YS Yield Strength
FF Ferrite Factor
1 Introduction

1.1 Introduction

Gas Tungsten Arc Welding (GTAW), also called Tungsten Inert Gas (TIG) welding, is a fusion-welding process that uses an inert gas to protect the weld zone from the oxidizing atmosphere [5]. An intense electric arc between a tungsten electrode and the workpiece provides the heat required for welding. A bare welding rod is fed either manually or automatically into the weld zone and melted with the base metal. GTAW easily welds all stainless steels; and it is suited for welding stainless steel pipes with or without an insert or a backing ring. It is also widely used in joining tubes to tube sheets in shell-to-tube heat exchangers [5].

1.2 Problem Statement

Literature on the filler metals for the welding of 3CR12 has shown that grade 309 filler wire is the preferred one. However, grade 308L, 316L, 309Mo and 309L have also been applied in many cases [7]. Fewer studies were done on 3CR12 electrode welding on 3CR12 compared with welding with 308L, 316L, 309Mo and 309L wires. This investigation compared welding 3CR12 with 308L, 316L, 309Mo, 309L and 3CR12 wires to determine whether using 3CR12 wire offers any benefits.

1.3 Aim and Objectives

The aim of this research was to determine the optimum welding material of 3CR12. Using the results obtained, the optimized filler metal will be achieved.

To achieve this aim, the following objectives were met:

1. A detailed study of the literature on welding of 3CR12 was conducted.
2. An experimental program was designed; this determined the effect of different welding wires on the mechanical performance of 3CR12 welds.
3. Experiments were conducted, which captured the performance of 3CR12 TIG welds conducted, using different welding wires.
4. The obtained experimental data were analyzed.
5. Conclusions and recommendations, based on the obtained results, were deduced.

1.4 Hypotheses

The compatibility of filler material with 3CR12 on mechanical performance was conducted, using different filler metals. The filler metals used included: E309L, E308L and E316L. Therefore, the hypothesis of this work was stated as: “Filler metals that could produce defect-free welded joints of 3CR12 and their ensuing mechanical properties were dependent on the welding process and the process parameters, such as welding current, nozzle and gas-flow rate”.

1.5 Methodology

To study the compatibility of filler material for 3CR12 on microstructure, hardness and tensile testing, 3CR12 was welded with different filler materials and tested. A 3CR12 stainless steel plate from Columbus Stainless Steel with a thickness of 2mm was used in this experiment. The 3CR12 material welded with different filler materials was used and analyzed; and the welded combination with the best results was selected.

The material characterization methods considered were: the microstructure, hardness, and the tensile testing of the joints.

1.6 Significance of the Research

Currently, some companies like Transnet and the Gold mines in South Africa use the 3CR12 due to its corrosion-resistance properties. 3CR12 is a specialty steel; thus its cost is higher than that of other corrosion-resistant stainless steels. Welding with 3CR12 filler rod increases the costs incurred in the use of the material. The research provided reliable options of welding 3CR12 with a filler material other than 3CR12. Academically, the study enriched the previous research programs done at the University of Johannesburg on a similar topic.
1.7 Research Outline

Chapter 1 consists of the introduction, the problem statement, the aim and objectives, hypothesis, methodology, and the significance of the research.

Chapter 2 presents the detailed literature review on TIG welding, filler materials, 3CR12 and the weld integrity. The previous studies done on this topic are included in this chapter. This work was used as a reference in moving forward with this investigation. Chapter 2 gives a guide to Chapter 3 by using it as a baseline for the experiments.

Chapter 3 presents the experimental set-up for the tests that were done in this study. This chapter also presents the experimental work performed and the results obtained.

Chapter 4 presents the results obtained from the experimental work and a discussion of the results together with a comparison with the findings of previous studies.

Chapter 5 presents the conclusion of the study, and some recommendations for future studies.
2 Literature Survey

2.1 Introduction

This chapter is a review of the literature relevant to this study. The first section of the survey discusses the welding processes to be used in this study – focusing on the Gas-Tungsten Arc Welding (GTAW) or Tungsten-Inert Gas (TIG) welding and TIG welding wires. The second part discusses the development of 3CR12, stainless steel phases, their weldability and heat treatment, the classification of 3CR12, the weldability of 3CR12, the welding parameters and the welding consumables. The third section of the study discusses the previous studies done on 3CR12.

2.2 The Welding Process

Welding is a metal-joining process. The welding processes are classified into two groups, namely: Fusion welding and Forge welding. Fusion welding is a welding process that utilizes only heat; while Forge welding is a welding process that utilizes a combination of heat and pressure [13].

2.2.1 Forge Welding

In forge welding, the parts are joined by first heating them to a required temperature in the furnace, and then hammering them together. Forge welding is similar to Electric-Resistance Welding, Spot Welding, Seam Welding, Projection Welding, Upset Welding and Flash Welding processes, which use the principle of applying heat and pressure [13].

2.2.2 Fusion Welding

In fusion welding, the parts joined are held in a position; while the molten metal is supplied to the joint. The molten metal may come from either the parent metal, or the filler metal, which may have the same composition as that of the parent metal. The joint is formed when
the molten metal solidifies or fuses [13]. The fusion welding is classified as thermite welding, gas welding and arc welding. This process is illustrated in Figure 2-1.

![Figure 2-1: Fusion Welding](image)

### 2.3 Arc Welding

Arc welding is a process, whereby heat is generated by an electric arc struck between two electrodes, or between an electrode and a workpiece. An electric arc is a luminous electrical discharge between two electrodes through ionized gas. The electric arc between the electrode and the workpiece closes the electric circuit and creates temperatures of up to 5500°C, which is sufficient for fusion to take place that enables the workpiece edges to join together. The weld pool is protected by the use of shielding gas, coatings, or fluxes [13]. Arc-welding processes [13] vary, as shown below:

- Carbon-Arc Welding (CAW)
- Shielded Metal-Arc Welding (SMAW)
- Flux Cored-Arc Welding (FCAW)
- Gas Tungsten-Arc Welding (GTAW)
- Gas Metal-Arc Welding (GMAW)
- Plasma-Arc Welding (PAW)
- Atomic-Hydrogen Welding (AHW)
- Electro-slag Welding (ESW)
- Stud Arc-Welding (SAW)
2.3.1 Welding Processes for Stainless Steel

The processes for welding stainless steels include Gas Tungsten-Arc Welding (GTAW or TIG), Plasma-Arc Welding (PAW), Shielded Metal-Arc Welding (SMAW or MMA), Gas Metal-Arc Welding (GMAW or MIG/MAG), Fluxed Core Arc Welding (FCAW or FCW), Submerged-Arc Welding (SAW), Electric-Resistance Welding (ERW) and Laser Welding.

2.3.1.1 Gas Tungsten Arc Welding (GTAW or TIG)

GTAW or TIG is the most widely used process, due to its versatility, high quality and the aesthetic appearance of the finished weld [15]. This has the ability to weld at low current; hence low heat input and the ability to add filler wire when required. This makes it ideal for welding thin materials and root runs in one-sided welding of thicker plates or pipes. GTAW or TIG process is easily mechanized and the ability to weld with or without the addition of filler wire makes it the ideal process for the orbital welding of pipe. Shielding gases used for GTAW or TIG include pure argon and argon-rich mixtures with the addition of hydrogen, helium, or nitrogen. Oxidation and the loss of corrosion resistance are eliminated by using the inert-backing gas protection of the weld under-bead with single-sided welding [15].

2.3.1.2 Plasma-Arc Welding (PAW)

PAW is a derivative of the TIG process, involving a constructed nozzle system to produce a narrow concentrated transferred-plasma arc with deep penetration characteristics. This process is mainly used in a mechanized system; where high speed and high productivity autogenous welding of square-edged butt joints of up to 8mm thick is required [15]. For the welding of thicker squared butt joints, a combination of PAW/TIG and filler wire becomes necessary – to ensure a full profile weld surface. Thicknesses greater than 10mm require a partial v-penetration PAW root weld, which is followed by multi-pass joint filing [15]. The corrosion resistance of the under-bead is maintained by the use of argon-backing gas protection.
2.3.1.3 Shield Metal-Arc Welding (SMAW or MMA)

SMAW or MMA is the oldest manual arc-welding process. MMA electrodes are used commonly, due to their flexibility in accommodating the wide range of materials to be welded. Electrode-coating types are produced to give performance characteristics, which make them suitable for different welding applications. The most widely used electrode is the acid rutile-coated electrode, which produces a spray arc-type metal transfer, self-releasing slag and a finely rippled aesthetic weld profile [15]. This process requires a minimal post-weld treatment. The acid rutile-coated electrodes are primarily used in a down-hand position when producing fillet and butt welds. The electrodes with this type of coating can be used in position; but they are limited in application and size of up to 3.2mm maximum [15].

Basic-coated electrodes produce weld metal of higher integrity, with slag micro-inclusions and gas pores; and they are extremely useful for fixed pipe welds. Slag removal and weld profiles are not as attractive as with the acid-rutile types. Special coated electrodes are produced for specific applications, like vertical down and high recovery down-hand welding.

2.3.1.4 Gas Metal-Arc Welding (GMAW or MIG/MAG)

GMAW or MIG/MAG is a semi-automatic welding process, which involves a continuous consumable solid wire electrode and an argon-rich shielding gas. It is used for its high productivity features, when welding thin material using a short-circuit metal transfer mode, or spray arc transfer with thicker material [15]. GMAW power sources, which produce a pulsed current supply have been developed to provide an improved weld metal quality with positional welding and cleaner weld appearance. The arc stability and weld-bead wetting characteristics are improved by the use of gas mixtures with the addition of oxygen, helium, or carbon dioxide [15].

2.3.1.5 Flux Cored-Arc Welding (FCAW or FCW)

FCAW or FCW is a version of the MIG/MAG process, where the solid wire consumable is replaced with a flux (FCM) or metal powder (MCM) filled tubular wire as shown in Figure 2-2; and this can be used with equipment of the same type [15]. Two types of wire are
produced; one is to provide all positional capabilities; and one is for higher deposition down-hand welding applications. Higher rates of weld deposition and weld-metal overlaying are possible than in the MMA or MIG/MAG process [15]. Significant reduction in post-weld cleaning and treatment is possible.

2.3.1.6 Submerged-Arc Welding (SAW)

SAW (Figure 2-3) is a fully mechanized wire and flux powder shielded-arc process capable of high deposition rate, fast travel speed and weld quality. SAW applications include continuous down-hand fillet and butt welds in thicker section plate, pipe, vessels and stainless steel cladding of carbon steel components, particularly where long seams and or extended runs are involved [15].
2.3.1.7 Electric-Resistance Welding (ERW)

ERW includes the resistance spot and seam welding. This process is generally restricted to the mass production of thinner material, with the overlap-joint type of weld configuration; and the resultant crevice will not detract from any corrosion resistance expected during service [15].

2.3.1.8 Laser Welding

Laser-beam welding (Figure 2-4) is a technique whereby two or more pieces of material are joined together through the use of a laser beam. The energy concentration reached in the focus spot of laser beam is very intense; and it is capable of producing deep penetrating welds in thick section stainless steel, with minimal component distortion [15]. This process uses high capital-cost equipment; thus its use is reserved for mass production [15].

Guidelines for selecting the welding process for stainless steel are presented in Table 2-1. This suggests that GTAW is a preferred process for welding stainless steel, based on the thicknesses of the material in question.
2.3.2 Gas Tungsten-Arc Welding (GTAW) or Tungsten Inert gas (TIG)

Gas Tungsten-Arc Welding (GTAW) or Tungsten Inert-Gas (TIG) welding was introduced in 1940 during the World War II; when the aircraft industry required a new method for welding magnesium and aluminium [12]. GTAW or TIG welding is a fusion-welding process that uses an inert gas to protect the weld zone from the atmosphere. An intense electric arc provides the heat between a non-consumable tungsten electrode and the workpiece. A bare welding rod is fed, either manually or automatically, into the weld zone; and melted with the base metal, as illustrated in Figure 2-5. GTAW or TIG easily welds stainless steel; and it is suitable for welding stainless steel pipes with or without an insert or backing ring; and it is also used in joining tubes and sheets in shell-and-tube heat exchangers.

In this process, filler metal is fed manually by the welder, which results in slow welding of thick components. Hot-wire GTAW can be used to increase the welding speed by automating the feeding process, and heating the filler rod by resistance heating, thereby achieving higher deposition rates.

![Figure 2-5: GTAW Welding, basic principle [49]](image-url)
The equipments are set up, as shown in Figure 2-6. A gas cylinder with supply to torch, torch connected to negative polarity of DC power source, return clamp and return cable from workpiece to positive polarity.

![Figure 2-6: GTAW Equipment Set up](image)

TIG’s advantages include: use in all positions; it is stable; intense and yields a well-directed heat supply, which ensures deep penetration and heat-affected zones; and it provides a clean, smooth weld of high quality, with little need for finishing (no slag). The TIG Welding is also used on thin-walled plates and pipes with thicknesses of up to 3mm [11].

More advantages of TIG welding [14] include:

- Narrow concentrated arc
- Able to weld ferrous and non-ferrous metals
- Does not use flux or leave a slag
- Uses a shielding gas to protect the weld pool and tungsten
- A TIG weld should have no spatter
- TIG produces no fume; but it can produce ozone

### 2.4 TIG wires

The selection of TIG wires used in TIG welding process depends on the following [14]:

- The composition of the material to be welded
• The mechanical properties of the weld material, and those that are a match for the base material
• Corrosion resistance should match
• Joint design
• Thickness of the base material
• Cost

2.5 Welding Parameters

The guidelines for the welding parameters applicable in the welding of stainless steels are shown in Table 2-2.

<table>
<thead>
<tr>
<th>Metal gauge</th>
<th>Joint type</th>
<th>Tungsten size</th>
<th>Filler rod size</th>
<th>Cup size</th>
<th>Shielding gas flow</th>
<th>Welding amperes</th>
<th>Travel speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6mm</td>
<td>Butt</td>
<td>1.6mm</td>
<td>1.6mm</td>
<td>4, 5, 6</td>
<td>Argon 11(5.5)</td>
<td>80-100</td>
<td>307mm</td>
</tr>
<tr>
<td></td>
<td>Fillet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90-100</td>
<td>256mm</td>
</tr>
<tr>
<td>3.2mm</td>
<td>Butt</td>
<td>1.6mm</td>
<td>2.4mm</td>
<td>4, 5, 6</td>
<td>Argon 11(5.5)</td>
<td>120-140</td>
<td>307mm</td>
</tr>
<tr>
<td></td>
<td>Fillet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>130-150</td>
<td>256mm</td>
</tr>
<tr>
<td>4.8mm</td>
<td>Butt</td>
<td>2.4mm</td>
<td>3.2mm</td>
<td>5, 6, 7</td>
<td>Argon 13(6)</td>
<td>200-250</td>
<td>307mm</td>
</tr>
<tr>
<td></td>
<td>Fillet</td>
<td>2.4mm</td>
<td>3.2mm</td>
<td></td>
<td></td>
<td>225-275</td>
<td>256mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.2mm</td>
<td></td>
<td></td>
<td></td>
<td>275-350</td>
<td>256mm</td>
</tr>
<tr>
<td>6.4mm</td>
<td>Butt</td>
<td>3.2mm</td>
<td>4.8mm</td>
<td>8, 10</td>
<td>Argon 13(6)</td>
<td>275-350</td>
<td>256mm</td>
</tr>
<tr>
<td></td>
<td>Fillet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>300-375</td>
<td>205mm</td>
</tr>
</tbody>
</table>

The welding current is an essential parameter required for good welding, together with the correct electrode, nozzle and gas-flow setting. Table 2-3 shows the welding current suitable for welding different material thicknesses. The actual current needed to form a proper molten pool depends partly on the size of the workpiece, the type of joint, and the amount of preheating used [11].
Table 2-3: Typical TIG Welding Parameters [11]

<table>
<thead>
<tr>
<th>Set 1</th>
<th>Set 2</th>
<th>Set 3</th>
<th>Set 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material thickness</strong></td>
<td>&lt;1.5mm</td>
<td>1.5 – 2.5mm</td>
<td>2.5 – 4.0mm</td>
</tr>
<tr>
<td><strong>Copper alloys</strong></td>
<td>1.0 – 1.5mm</td>
<td>1.5 – 2.5mm</td>
<td>&gt;2.5mm</td>
</tr>
<tr>
<td><strong>Welding current, DC, electrode</strong></td>
<td>20 – 70A</td>
<td>50 – 120A</td>
<td>100 – 180A</td>
</tr>
<tr>
<td><strong>Gas flow, Pure argon</strong></td>
<td>6l/min</td>
<td>7l/min</td>
<td>8l/min</td>
</tr>
<tr>
<td><strong>Electrode point angle</strong></td>
<td>35°</td>
<td>45°</td>
<td>60°</td>
</tr>
<tr>
<td><strong>Collet size, diameter of electrode</strong></td>
<td>1.6mm</td>
<td>1.6mm</td>
<td>2.4mm</td>
</tr>
<tr>
<td><strong>Collet body, size diameter of opening</strong></td>
<td>1.6mm</td>
<td>1.6mm</td>
<td>2.4mm</td>
</tr>
<tr>
<td><strong>Nozzle number and diameter of opening</strong></td>
<td>No. 6 (9mm)</td>
<td>No. 6 (9mm)</td>
<td>No. 7 (11mm)</td>
</tr>
<tr>
<td><strong>Tungsten electrode size</strong></td>
<td>1.6mm</td>
<td>1.6mm</td>
<td>2.4mm</td>
</tr>
</tbody>
</table>

Table 2-4 shows the different material thicknesses with the suitable types of joints, welding current and the size of the tungsten electrodes for stainless steel.
2.5.1 Welding problems and defects: causes and remedies

This section lists the different welding problems and defects; it also suggests the causes and remedies to these problems and defects. Welding defects covered include spatter, deformation, longitudinal cracks in the HAZ, arc striking, lack of fusion, rater cracks, undercut, porosity, slag inclusions and lack root penetration.

2.5.1.1 Spatter

This is a defect formed during welding; where metal drops fall on the base metal and on the weld rendering the surface not smooth, as illustrated in Figure 2-7 [60]. This defect might be caused by a high welding current, a very long arc length, an incorrect polarity, or even an
insufficient gas shield. The spatter can be minimized by correcting the welding conditions; and it could be eliminated by grinding [56].

![Figure 2-7: Spatter Defects [56]](image)

### 2.5.1.2 Deformation
Deformation is shown in Figure 2-8. It is also referred to as distortion in welding; it results from the expansion and contraction of the weld metal and the adjacent base metal during the heating and cooling cycle of the welding process [60]. Distortion can be eliminated by welding on both sides [56].

![Figure 2-8: Deformation Defects [56]](image)

### 2.5.1.3 Longitudinal cracks in the heat-affected zone
Longitudinal cracks are cracks shown in Figure 2-9, which occur due the cooling of the weld elements at different rates. These cracks can also be caused by: a weld bead that is too wide; current or welding speed that is too high; or by a root gap that is too large. These can also be caused by shrinkage stresses in areas of high constraint. Longitudinal cracks can be prevented by welding on areas of less constraint, preheating the elements; and also by using the correct welding consumables. The cracks could be repaired by grinding out or gouging and re-welding [60].

![Figure 2-9: Longitudinal Cracks in the HAZ Defects [56]](image)
2.5.1.4 Arc-striking difficulties

Arc strikes are localized spots that appear on the re-melted metal, as shown in Figure 2-10. These are caused by excessive force when using a chipping hammer, careless handling of the welding-electrode holder and from careless arc manipulation. Arc strikes can initiate cracks in the heat-affected zone of the weld metal; and they can cause localized stress concentrations [55].

![Arc strikes](image)

Figure 2-10: Arc-Striking Difficulties and Defects [55]

2.5.1.5 Solidification cracks

Solidification cracks occur only in the weld metal; and they appear as straight lines along the centreline of the weld bead, as shown in Figure 2-11 [60]. These cracks can be caused by insufficient weld bead size or shape, welding under high restraint, material with a high impurity content, or large amounts of shrinkage on solidification. Solidification cracks can be prevented by cleaning the parent materials, or by using the correct welding parameters [56].

![Solidification Cracks](image)

Figure 2-11: Solidification Cracks as Defects [56]

2.5.1.6 Lack of fusion defects

Lack of fusion occurs when the gap between the base metals is not totally filled with molten metal, as shown in Figure 2-12. This happens due to the inaccuracy of the welder before solidification of the welding metal. Lack of fusion can be minimized by correct welding
conditions, such as the positioning of the electrode, reducing the deposition rate, or increasing the welding current; and decreasing the travel speed [56].

2.5.1.7 Crater cracks
Crater cracks are cracks, which occur at the end of the weld – due to improper weld terminations, as shown in Figure 2-13. These cracks can be prevented by applying the correct welding techniques [60].

2.5.1.8 Undercut
Undercut occurs; when the base metal melts away from the weld zone, forming a groove in the shape of a sharp recess, or notch, as shown in Figure 2-14. This defect reduces the fatigue strength of the joint [60]. Undercut can be prevented by adjusting the welding parameters.

2.5.1.9 Porosity
Porosity is a defect formed when air bubbles or gases are present in the weld zone, as shown in Figure 2-15; the distribution of air bubbles in the weld zone is random [60]. This defect is caused by gases release during the melting of the weld area; but they are trapped during solidification, by contamination or chemical reaction during welding. Porosity can be minimized by the proper selection of electrode, filler material or improved welding techniques [56].
2.5.1.10 Slag inclusions
Slag inclusions are compounds such as oxides, fluxes and the electrode that contains material that is trapped in the weld zone, as shown in Figure 2-16. These defects can be caused by insufficient cleaning between the multi-pass welds, incorrect electrode and current [60]. The slag inclusions might initiate cracking and reduce the cross-section area strength of the joint. These defects can be repaired by grinding down or gouging out and re-welding [56].

2.5.1.11 Lack of root penetration
Lack of root penetration occurs when the depth of the welded joint is insufficient [60], as shown in Figure 2-17. These defects are caused by incorrect welding conditions; and it could be prevented by applying correct welding conditions. Lack of penetration can be repaired by grinding or gouging out the defective arc and re-welding the joint [56].

It is then concluded from the literature on section 2.5.1 that the weld defects have an impact on the performance of the weld; thus, it is vital that the defects are eliminated.
2.6 Gas Tungsten-Arc Welding (GTAW) Joint Configurations

Gas Tungsten-Arc Welding (GTAW) is applicable for different joint designs, such as the butt, lap and tee joints. Figure 2-18 shows the different joint configurations.

![Figure 2-18: Weld Positions and Joints for GTAW](image)

The general requirements for GTAW of stainless steels, according to the thickness of the base metal, the joint configuration, and the welding position, are shown in Table 2-5. Cleanliness of the joint area is vital in welding of stainless steel.

**Table 2-5: General Requirements for GTAW Welding of Stainless Steel [5]**

<table>
<thead>
<tr>
<th>Thickness, in.</th>
<th>Type of Weld</th>
<th>Characteristics</th>
<th>Welding Current</th>
<th>Electrode Diameter, in.</th>
<th>Welding Speed, ipm</th>
<th>Rod Size, in.</th>
<th>Argon Gas Flow, cfm</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/16</td>
<td>1, 2 Butt</td>
<td>Flat</td>
<td>85-100</td>
<td>70-90 up</td>
<td>1/16</td>
<td>12</td>
<td>1/16</td>
<td>10</td>
</tr>
<tr>
<td>1/16</td>
<td>5, 6 Lap</td>
<td>Flat</td>
<td>100-120</td>
<td>90-110 up</td>
<td>1/16</td>
<td>10</td>
<td>1/16</td>
<td>10</td>
</tr>
<tr>
<td>1/8</td>
<td>7 Corner</td>
<td>Flat</td>
<td>100-120</td>
<td>90-110 up</td>
<td>1/16</td>
<td>10</td>
<td>1/16</td>
<td>10</td>
</tr>
<tr>
<td>1/8</td>
<td>8, 9 Fillet</td>
<td>Flat</td>
<td>100-120</td>
<td>90-110 up</td>
<td>1/16</td>
<td>10</td>
<td>1/16</td>
<td>10</td>
</tr>
<tr>
<td>1/4</td>
<td>1, 2 Butt</td>
<td>Flat</td>
<td>100-120</td>
<td>90-110 up</td>
<td>1/16</td>
<td>12</td>
<td>1/16 or 1/32</td>
<td>10</td>
</tr>
<tr>
<td>1/4</td>
<td>5, 6 Lap</td>
<td>Flat</td>
<td>110-130</td>
<td>100-120 up</td>
<td>1/16</td>
<td>10</td>
<td>1/16 or 1/32</td>
<td>10</td>
</tr>
<tr>
<td>1/4</td>
<td>7 Corner</td>
<td>Flat</td>
<td>100-120</td>
<td>90-110 up</td>
<td>1/16</td>
<td>12</td>
<td>1/16 or 1/32</td>
<td>10</td>
</tr>
<tr>
<td>1/4</td>
<td>8, 9 Fillet</td>
<td>Flat</td>
<td>110-130</td>
<td>100-120 up</td>
<td>1/16</td>
<td>10</td>
<td>1/16 or 1/32</td>
<td>10</td>
</tr>
<tr>
<td>1/2</td>
<td>1, 2 Butt</td>
<td>Flat</td>
<td>120-140</td>
<td>110-130 up</td>
<td>1/16</td>
<td>12</td>
<td>1/16</td>
<td>10</td>
</tr>
<tr>
<td>1/2</td>
<td>5, 6 Lap</td>
<td>Flat</td>
<td>130-150</td>
<td>120-140</td>
<td>1/16</td>
<td>12</td>
<td>1/16</td>
<td>10</td>
</tr>
<tr>
<td>1/2</td>
<td>7 Corner</td>
<td>Flat</td>
<td>120-140</td>
<td>110-130 up</td>
<td>1/16</td>
<td>12</td>
<td>1/16</td>
<td>10</td>
</tr>
<tr>
<td>1/2</td>
<td>8, 9 Fillet</td>
<td>Flat</td>
<td>130-150</td>
<td>120-140</td>
<td>1/16</td>
<td>12</td>
<td>1/16</td>
<td>10</td>
</tr>
<tr>
<td>1/2</td>
<td>9 Butt</td>
<td>Flat</td>
<td>200-250</td>
<td>150-200 up</td>
<td>1/8</td>
<td>10</td>
<td>1/16</td>
<td>15</td>
</tr>
<tr>
<td>1/2</td>
<td>6 Lap</td>
<td>Flat</td>
<td>225-275</td>
<td>175-225</td>
<td>1/8</td>
<td>10</td>
<td>1/16</td>
<td>15</td>
</tr>
<tr>
<td>1/2</td>
<td>7 Corner</td>
<td>Flat</td>
<td>200-250</td>
<td>150-200 up</td>
<td>1/8</td>
<td>10</td>
<td>1/16</td>
<td>15</td>
</tr>
<tr>
<td>1/2</td>
<td>8, 9 Fillet</td>
<td>Flat</td>
<td>225-275</td>
<td>175-225</td>
<td>1/8</td>
<td>10</td>
<td>1/16</td>
<td>15</td>
</tr>
<tr>
<td>3/4</td>
<td>2, 3 Butt</td>
<td>Flat</td>
<td>275-350</td>
<td>200-250 up</td>
<td>1/8</td>
<td>1/16</td>
<td>15</td>
<td>1 or 2 passes</td>
</tr>
<tr>
<td>3/4</td>
<td>6 Lap</td>
<td>Flat</td>
<td>300-375</td>
<td>225-275</td>
<td>1/8</td>
<td>1/16</td>
<td>15</td>
<td>1 or 2 passes</td>
</tr>
<tr>
<td>3/4</td>
<td>7 Corner</td>
<td>Flat</td>
<td>200-250</td>
<td>200-250</td>
<td>1/8</td>
<td>1/16</td>
<td>15</td>
<td>1 pass</td>
</tr>
<tr>
<td>3/4</td>
<td>6, 10 Fillet</td>
<td>Flat</td>
<td>300-375</td>
<td>225-275</td>
<td>1/8</td>
<td>1/16</td>
<td>15</td>
<td>3 passes</td>
</tr>
<tr>
<td>3/4</td>
<td>8, 10 Fillet</td>
<td>Flat</td>
<td>375-475</td>
<td>230-280</td>
<td>1/8</td>
<td>1/16</td>
<td>15</td>
<td>3 passes</td>
</tr>
</tbody>
</table>

*Note: The table includes welding parameters and considerations for different joint configurations.*
2.7 Stainless Steel

Stainless steels are iron-based alloys containing a minimum of 10.5% chromium, which forms a protective self-healing oxide film, thus making them corrosion resistant. Other alloying elements are often added to improve the properties of the stainless steel [21]. The categorization of stainless steel is based on the nature of their metallurgical structure. The metallurgical structure is the arrangement of the atoms making up the grains of the steel that are observed when a polished section through a piece of the material is viewed at high magnification through a microscope. The microstructure is formed, based on the chemical composition of the steel. The formed microstructure may be the stable phase’s austenite or ferrite, a duplex mix of these two, or the martensite phase [21]. These stainless steel phases are shown in Figure 2-19.

![Figure 2-19: Stainless Steel Phases [21]](image)

2.7.1 Weldability of Ferritic Stainless Steel

Ferritic stainless steels do not have good welding properties, due to the excessive grain growth, sensitization and their lack of ductility. Some of these problems can be minimized by post-weld heat treatment. Filler metals for ferritic stainless steels can be of a similar composition or from austenitic grade, such as Grade 308L, 309, 316L or 310. The austenitic
grade filler metals will improve the toughness of the weld. Most grades are welded in thin gauges to avoid the problem of excessive grain growth. The stabilized ferritic grades, such as 409 and 430Ti provide better weldability than the unstabilised alternatives, such as 430. Austenitic grades are readily weldable than ferritic stainless steels [21].

3CR12 is a proprietary ferritic grade with a very low carbon content; and it has a mill processing route balanced to enable welding. 3CR12 is readily welded even in heavy-section plate. It is normal for other ferritic stainless steels to use austenitic stainless steel fillers [21].

Table 2-6 stipulates the recommended filler metals for different stainless steel grades.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Pre-heat</th>
<th>Post Weld Heat Treatment</th>
<th>Filler</th>
</tr>
</thead>
<tbody>
<tr>
<td>304</td>
<td>Unnecessary for steel &gt;20°C</td>
<td>Cool rapidly from 1010 - 1090°C if corrosion condition severe</td>
<td>308L</td>
</tr>
<tr>
<td>304L</td>
<td>Unnecessary for steel &gt;20°C</td>
<td></td>
<td>308L</td>
</tr>
<tr>
<td>309</td>
<td>Unnecessary for steel &gt;20°C</td>
<td>Usually unnecessary as this grade is generally used at high temperatures</td>
<td>309</td>
</tr>
<tr>
<td>310</td>
<td>Unnecessary for steel &gt;20°C</td>
<td>As for 309</td>
<td>310</td>
</tr>
<tr>
<td>316</td>
<td>Unnecessary for steel &gt;20°C</td>
<td>Cool rapidly from 1060 - 1150°C if corrosion condition severe</td>
<td>316L</td>
</tr>
<tr>
<td>316L</td>
<td>Unnecessary for steel &gt;20°C</td>
<td>Not required</td>
<td>316L</td>
</tr>
<tr>
<td>321</td>
<td>Unnecessary for steel &gt;20°C</td>
<td>Not required</td>
<td>347</td>
</tr>
<tr>
<td>347</td>
<td>Unnecessary for steel &gt;20°C</td>
<td>Not required</td>
<td>347</td>
</tr>
<tr>
<td>S30815</td>
<td>Unnecessary for steel &gt;20°C</td>
<td>Not required</td>
<td>S30815 or 309</td>
</tr>
<tr>
<td>410</td>
<td>Preheat at 200 - 320°C</td>
<td>Air cool from 650 - 760°C</td>
<td>410, 308L, 309 or 310</td>
</tr>
<tr>
<td>430</td>
<td>Preheat at 200 - 320°C</td>
<td>Air cool from 650 - 760°C</td>
<td>430, 308L, 309 or 310</td>
</tr>
<tr>
<td>434</td>
<td>Preheat at 200 - 320°C</td>
<td>Air cool from 760 - 790°C</td>
<td>430, 308L, 309 or 310</td>
</tr>
<tr>
<td>3CR12</td>
<td>Not required</td>
<td></td>
<td>309, 309L, 309Mo, 309MoL, 316L or 308L</td>
</tr>
<tr>
<td>2205</td>
<td>Pre-heat at 50°C when temperature is &lt;10°C</td>
<td>Not generally required</td>
<td>2209</td>
</tr>
</tbody>
</table>
2.7.2 Heat Treatment

All martensitic and most ferritic stainless steels can be sub-critically annealed or process annealed by heating into the upper part of the ferrite temperature range, or fully annealed by heating above the critical temperature into the austenite range, followed by slow cooling. Sub-critical annealing occurs at temperatures of 760°C to 830°C [21].

Stainless steels are annealed in controlled atmospheres to prevent or reduce scaling. The treatment can be in salt bath; but bright annealing is preferred in a highly reduced atmosphere. Bright annealing is applicable on products like flat, rolled coil, tube and wire in an atmosphere of nitrogen and hydrogen. This results in a surface requiring no scale removal as before annealing [21].

Austenitic stainless steel contains at least 16% chromium and 6% nickel; and they range through to the high alloy or super austenitics, such as 904L and 6% molybdenum grades. Alloying elements, like molybdenum, titanium or copper can be added to improve the properties of the steel; and to make it suitable for critical applications involving high temperature and corrosion-resistance [21].

Ferritic stainless steels are steels containing 10.5% to 18% chromium, such as grades 430 and 409 [21]. The steel has moderate corrosion resistance and poor fabrication properties; but they have been improved in the higher grades, such as 434, 444, and 3CR12.

Martensitic stainless steels are steels containing major alloying elements with a higher carbon and generally lower chromium content (like 12% in Grades 410 and 416) than the ferritic types.

Duplex stainless steel are steels containing 20 - 22% chromium, 3.5 - 5% nickel, and containing further minor-alloying elements. The steels have a microstructure comprising of a mixture of austenite and ferrite. Duplex ferritic-austenitic steels have a combination of properties of other stainless steel classes; the steel is resistant to stress-corrosion cracking; but it is not as resistant as ferritic steels. It has toughness superior to that of austenitic steels; and its strength is greater than that of the annealed austenitic steel by a factor of two [21].
2.7.3 Development of 3CR12

3CR12 was developed by Middelburg Steel & Alloys (MS&A), the forerunner of Columbus Stainless Steel in the 1970s, from AISI 409 ferritic stainless steel. The need came as the mining industry was looking for a way of introducing affordable corrosion-resistant steel. 3CR12 was three times more expensive than mild steel in the late 70s; but its price then dropped significantly to a ratio of about 2:1 [16]. However, 3CR12 only costs about 20% more than galvanized steel; and its life span is 10 times as long. The life-cycle costing of 3CR12 ensures that it pays for itself earlier. 3CR12 has since been used as the material of choice in mining applications, the sugar industry, coal wagons, buses and others [16].

Comparison of 3CR12 with other stainless steels showed that the scrap and reworks were high and surface defects and embrittlements were problematic. These problems were addressed by optimizing the process routes, annealing temperatures and line speeds between 1986 and 1995. During 1996 to 2005, four types of 3CR12 were developed; 3Cr12 (409W + Ni alloy), 3Cr12Ti (3Cr12 +Ni + Ti alloys), 3Cr12L (3CR12 – Ni – Ti alloy), and 3Cr12LT (3Cr12L + Ni) [16]. Figure 2-20 describes these 3CR12 versions with their advantages.

![Figure 2-20: 3CR12 Categories](image)

Columbus Stainless routinely produces two versions, namely: 3CR12 and 3CR12L). The other two versions can be produced for specific applications [16].

The compositional development of 3CR12 is stipulated in Table 2-7.
2.7.4 Classification of Type 3CR12

3CR12 is a corrosion-resistant (ferritic stainless) steel containing 12% chromium, which has been developed from AISI 409 stainless steel. The carbon and nitrogen content are kept low, in order to enhance the toughness in 3CR12. Most ferritic-type stainless steels have a chromium content of 11.5% to 18%. The absence of a high percentage of nickel gives the alloy its ferritic structure. This is due to the chromium operating as a ferritic stabilizer. These steels are hardened partly by cold work of forming; and they are not hardened by a heat treatment. Ferritic stainless steels are magnetic; and they develop a maximum softness, ductility and corrosion resistance in the annealed state [20].

The development of 3CR12 corrosion resisting steel was as a result of the need to obtain a low-chromium containing steel with better mechanical properties and weldability than that of AISI 409 stainless steel [20]. It is also developed as an alternative material of construction, where the mechanical properties, the corrosion resistance and the fabrication requirements of other materials, such as mild steel, galvanized or aluminized steel, aluminium or pre-painted steels are not suitable [2].

The advantages of 3CR12 are that it has a high strength – even when welded in thicknesses of up to 30mm; and it retains the toughness at temperatures below freezing point [1]. 3CR12 may stain when exposed to aggressive atmospheric conditions; thus painting is recommended in applications where aesthetic appearance is vital [1]. 3CR12 is used in material handling, road transport, rail transport, petrochemicals and chemicals, power generation, telecommunication cabinets and electrical enclosures and water- and sewage-treatment plants [1].

The chemical composition of 3CR12 is shown in Table 2-8. The mechanical properties of 3CR12 are shown in Table 2-9. 3CR12 is recommended to operate up to a maximum of 620°C, when operated continuously; and 730°C, when operated intermittently. Table 2-10 shows the creep properties of 3CR12.

<table>
<thead>
<tr>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>Ni</th>
<th>Si</th>
<th>Ti</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,025</td>
<td>11</td>
<td>1</td>
<td>0,5</td>
<td>1</td>
<td>0,75</td>
<td>-</td>
</tr>
<tr>
<td>0,025</td>
<td>1,5</td>
<td>1,2</td>
<td>0,6</td>
<td>0,5</td>
<td>0,3</td>
<td>0,02</td>
</tr>
<tr>
<td>0,025</td>
<td>11,5</td>
<td>1</td>
<td>0,1</td>
<td>0,5</td>
<td>0</td>
<td>0,02</td>
</tr>
</tbody>
</table>

Table 2-7: Compositional Development of 3CR12 [22]
### Table 2-8: Chemical Properties of 3CR12 [1]

<table>
<thead>
<tr>
<th>Type</th>
<th>%C</th>
<th>%Si</th>
<th>%Mn</th>
<th>%P</th>
<th>%S</th>
<th>%Cr</th>
<th>%Ni</th>
<th>%N</th>
<th>%Ti</th>
<th>4(C+N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3CR12</td>
<td>0.030 max</td>
<td>1.00 Max</td>
<td>2.00 max</td>
<td>0.040 max</td>
<td>0.030 max</td>
<td>10.50 max</td>
<td>1.50</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2-9: Mechanical Properties of 3CR12 [1]

<table>
<thead>
<tr>
<th>Type</th>
<th>Product Form or Gauge (mm)</th>
<th>0.2% proof Stress (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Elongation (%)</th>
<th>Brinell Hardness</th>
<th>Impact Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3CR12</td>
<td>&lt;3</td>
<td>280</td>
<td>460 min</td>
<td>20 min</td>
<td>220 max</td>
<td>35x10^4</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 to 4.5</td>
<td>300</td>
<td>460 min</td>
<td>20 min</td>
<td>220 max</td>
<td>35x10^4</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;4.5 to 12</td>
<td>300</td>
<td>460 min</td>
<td>20 min</td>
<td>220 max</td>
<td>35x10^4</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;12</td>
<td>300</td>
<td>460 min</td>
<td>20 min</td>
<td>250 max</td>
<td>35x10^4</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2-10: Creep Properties of 3CR12 [1]

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Stress to produce 1% strain (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000 hours</td>
</tr>
<tr>
<td>400</td>
<td>315</td>
</tr>
<tr>
<td>450</td>
<td>195</td>
</tr>
<tr>
<td>500</td>
<td>88</td>
</tr>
<tr>
<td>550</td>
<td>34</td>
</tr>
</tbody>
</table>
The welded joints of 3CR12 using austenitic steel electrodes have fatigue strength similar to that of identical joints in construction steels, such as BS4360 Grade 43A [1]. Table 2-11 shows the physical properties of 3CR12.

Table 2-11: Physical Properties of 3CR12 [1]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7680kg/m³</td>
</tr>
<tr>
<td>Specific Heat Capacity</td>
<td>478J/kgK</td>
</tr>
<tr>
<td>Thermal Conductivity @ 100°C</td>
<td>30.0W/mK</td>
</tr>
<tr>
<td>@ 500°C</td>
<td>40.0W/mK</td>
</tr>
<tr>
<td>Electrical Resistivity</td>
<td>678nΩ</td>
</tr>
<tr>
<td>Mean Co-efficient of Thermal Expansion: 0 - 100°C</td>
<td>11.1μm/mK</td>
</tr>
<tr>
<td>0 - 300°C</td>
<td>11.7μm/mK</td>
</tr>
<tr>
<td>0 - 500°C</td>
<td>12.3μm/mK</td>
</tr>
<tr>
<td>Melting Range</td>
<td>1430 - 1510°C</td>
</tr>
<tr>
<td>Relative Permeability</td>
<td>Ferromagnetic</td>
</tr>
</tbody>
</table>

2.8 Weldability of 3Cr12

3CR12 has good weldability. It can be welded to other ferrous metals, like mild steel and stainless steel by using standard welding methods, like Manual Metal-Arc welding (MMA), Metal Inert-Gas welding (MIG), Tungsten Inert-Gas welding (TIG), Flux-Cored Arc Welding (FCAW), and Plasma-Arc welding (PAW). It is recommended that AWS 309L type be used as an electrode, when welding 3CR12 to other ferrous materials, rather than using the ones that match either of the base metals. This is to avoid excessive weld metal dilution [2]. Electrodes E308L and E316L are recommended for welding 3CR12 to itself. During welding, the heat input should be controlled between 0.5kJ and 1.5kJ per pass. The weld discoloration should be removed by pickling and passivation to restore the maximum corrosion resistance [2].
2.9  Welding Consumables for 3CR12

In Tungsten Inert-Gas welding, heat is produced by an electric arc that is struck between a Tungsten electrode and the work piece. The welding rod is added to the welding pool to produce a weld build-up. The welding rod is normally made of a metal similar to the welded metal. The tungsten electrode will not melt, despite the very high temperatures; but it will gradually be consumed during ignition – and to some extent during the actual work [9].

2.9.1  Afrox 3CR12 Electrode

Afrox’s 3CR12 is a chromium-alloyed electrode suitable for all-position welding of 13% chromium ferritic steels. The 3CR12 electrode has a low inclusion content; and it exhibits good toughness at low temperatures down to -20°C. The electrode features a smooth, stable, low spatter arc on DC+. It has a good weld bead appearance, with a smooth uniform ripple. Afrox E3CR12 has been developed specially for the welding of 3CR12 material. The Afrox 3CR12 weld metal has similar corrosion-resistant properties to that of 3CR12, without over-alloying, compared to the 300 series electrodes [10]. Table 2-12 and Table 2-13 list the chemical properties and mechanical properties of Afrox’s 3CR12 electrode, respectively.

<table>
<thead>
<tr>
<th>Chemical Analysis</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.04 max.</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.5 - 1.0</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.45 max.</td>
</tr>
<tr>
<td>Chromium</td>
<td>12.0 – 13.0</td>
</tr>
<tr>
<td>Nickel</td>
<td>4.0 – 5.0</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.40 – 0.70</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.020 max.</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.025 max.</td>
</tr>
</tbody>
</table>
Table 2-13: Mechanical Properties of Afrox's 3CR12 Electrode [10]

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tensile Strength</strong></td>
<td>900 – 1150 MPa</td>
</tr>
<tr>
<td><strong>0.2% Proof Stress</strong></td>
<td>700 MPa</td>
</tr>
<tr>
<td><strong>Elongation on 5d</strong></td>
<td>10 – 15%</td>
</tr>
<tr>
<td><strong>Charpy V-Notch at 20°C</strong></td>
<td>40 – 55J</td>
</tr>
<tr>
<td><strong>Charpy V-Notch at -20°C</strong></td>
<td>25 – 35J</td>
</tr>
</tbody>
</table>

2.9.2 309L-17 Electrode

The 309L-17 type stainless steel electrode is a rutile type of stainless steel electrode with outstanding operator appeal and improved slag lift. It is designed for all positional-welding capabilities, except the vertical down position. It is applied on the single and multi-pass welding of molybdenum-bearing stainless steels, 316, 316L, and the general purpose welding of other “300 series” austenitic stainless steels, including 3CR12 [8].

2.9.3 309Mo-16 Electrode

309Mo-16 is a stainless steel electrode containing molybdenum-bearing highly alloyed 23Cr/12Ni/2.5Mo extra-low carbon rutile as shown in Table 2-14. It exhibits superior all positional (except vertically down) performance, with an improved moisture-resistant coating for weld metal of high radiographic integrity. 309Mo-16 promotes exceptional weld appearance and profile by its smooth arc action, low spatter and excellent slag control/detachability. This electrode is recommended for the welding of matching 309 and 309 Mo-based metals and a wide range of 300 and 400 series stainless steels to alloy and non-alloyed dissimilar ferrous-metal combinations, provided the service temperature is below 400°C [3, 4].

309L is mainly used under high dilution conditions. 309L could also be used for welding 12% Cr utility ferritic alloys, such as 3CR12, to itself and to other steels. Weld metal with controlled high carbon and low ferrite should be used for welding high-temperature structural service [3]. The mechanical properties of 309Mo-16 are shown in Table 2-15.
### Table 2-14: Chemical Properties of 309Mo-16 Electrode [4]

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>0.8</td>
<td>0.7</td>
<td>23.5</td>
<td>13.0</td>
<td>2.4</td>
<td>Bal</td>
</tr>
</tbody>
</table>

### Table 2-15: Mechanical Properties of 309Mo-16 electrode [4]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Stress</td>
<td>400MPa</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>670MPa</td>
</tr>
<tr>
<td>Elongation</td>
<td>38%</td>
</tr>
</tbody>
</table>

### 2.9.4 316L-16 Electrode

316L-16 is a molybdenum-bearing 19Cr/12Ni/2.5Mo extra low carbon-rutile electrode as shown in Table 2-16. This electrode exhibits superior all-positional (except vertically down) performance, with an improved moisture-resistant flux coating for weld metal of high radiographic integrity [4]. 316L-16 promotes exceptional weld appearance and profile by its smooth arc action, low spatter and excellent slag control/detachability. It also provides high arc stability and easy restriction on low voltage AC welding machines. This electrode is recommended for welding 316, 316L and common 300 series stainless steels, such as 301, 302, 304, and 304L. It is also suitable for welding ferritic stainless-steel alloys like 3CR12 [4]. The mechanical properties of 309Mo-16 are shown in Table 2-17.

### Table 2-16: Chemical Properties of 316 L-16 Electrodes [4]

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>0.7</td>
<td>0.7</td>
<td>18.5</td>
<td>12.0</td>
<td>2.4</td>
<td>Bal</td>
</tr>
</tbody>
</table>
Table 2-17: Mechanical Properties of 316L-16 Electrodes [4]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Stress</td>
<td>380MPa</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>600MPa</td>
</tr>
<tr>
<td>Elongation</td>
<td>40%</td>
</tr>
</tbody>
</table>

2.10 Microstructure Morphology

2.10.1 Ferrite

Ferrite is essentially a solid solution of iron, containing carbon, or one or more alloying elements, such as silicon, chromium, manganese and nickel. There is an interstitial solid solution and a substitutional solid solution. In an interstitial solid solution, elements with small atomic diameters like carbon and nitrogen, occupy specific interstitial sites in the body-centred cubic (bcc) iron-crystalline lattice. Elements with similar atomic diameters, like manganese and nickel replace or substitute the iron atoms in a substitutional solid solution [51]. The microstructure of ferrite is shown in Figure 2-21.

![Figure 2-21: Microstructure of fully ferritic, ultralow carbon steel. Marshalls etch + HF, 300x [51]](image)

2.10.2 Pearlite

Pearlite is formed when the carbon content of steel is increased beyond the solubility limit (0.02% C) on the iron-carbon binary phase diagram shown in Figure 2-22. The pearlite is formed by the cooling of steel through the eutectoid temperature (the temperature of 727°C)
forming cementite and ferrite, as parallel plates called lamellae. The microstructures in Figure 2-23 and Figure 2-24 consist of a hard carbide phase, cementite, and a very soft ductile ferrite phase. A fully pearlitic microstructure is formed at the eutectoid composition of 0.78%C [51]. The fully pearlitic steels have high strength, high hardness and good wear resistance. However, they also have poor ductility and poor toughness. [51]

Figure 2-22: Iron-carbon phase diagram showing the austenite (γFe) and ferrite (αFe) phase regions and eutectoid composition and temperature. Dotted lines represent iron-graphite equilibrium conditions and the solid lines represent iron-cementite equilibrium conditions. Only the solid lines are important with respect to steels. [51]

Figure 2-23: Microstructure of a typical fully pearlitic rail steel showing the characteristic fine pearlite interlamellar spacing. 2% nital + 4% picral etch. 500x. [51]
2.10.3 Ferrite-Pearlite

The ferrite-pearlite microstructure is shown in Figure 2-25. The microstructure and the properties of ferrite-pearlite steel are determined by the carbon content and the grain size. Figure 2-26 illustrates the effect of carbon content on the tensile and on the impact properties. This relationship shows that the ultimate tensile strength steadily increases with the increase in carbon content. This is caused by an increase in volume fraction of pearlite in the microstructure. The strength of the pearlite is much higher than that of the ferrite [51].

The relationship of the yield strength with respect to the carbon content shows that the yield strength is relatively unaffected by the carbon content. The yielding in ferrite-pearlite steel is controlled by the ferrite matrix, which is considered to be a continuous phase in the microstructure; thus pearlite has a minor effect on the yielding behaviour [51].
Bainite is a composite of ferrite and cementite. The ferrite has an acicular morphology and the carbides are discrete particles, which differentiate it from the pearlite. Bainitic steels have high strength with good toughness; whereas pearlitic steels have high strength with poor toughness. Bainite has two morphologies in Figure (Figure 2.6) namely upper bainite and lower bainite, which depend on the temperature regions at which bainite formed during isothermal transformation [51]. Upper bainite is formed isothermally in the temperature range of 400 to 550 °C; and lower bainite was formed isothermally in the temperature range of 250 to 400 °C. The iron carbide phase forms at the lath boundaries in upper bainite, whereas the carbide phase forms on particular crystallographic planes within the laths in the lower bainite. The lower bainites possess higher strength and higher toughness than upper bainite with a coarse structure, because of its fine acicular structure and the carbides within the laths. [51]
Martensite as shown in Figure 2-28 is a supersaturated solid solution of carbon in iron. The amount of carbon in martensite far exceeds that found in solid solution in ferrite, which makes the normal body-centred cubic (bcc) lattice to distort, in order to accommodate the carbon atoms. The distorted lattice becomes body-centred tetragonal (bct). This supersaturation is generally produced through very rapid cooling from the austenite phase region, in order to avoid the formation of ferrite, pearlite and bainite [51].
2.10.6  **Austenite**

Austenite does not exist at room temperature in plain-carbon and low alloy steels; but it only exists in small amounts of retained austenite that did not transform during rapid cooling. Austenite is the face-centred cubic alloy (fcc), as compared with ferrite, which has a bcc lattice. A fcc alloy has low-temperature toughness, excellent weldability; and it is corrosion-resistant. However, austenitic steels are susceptible to stress-corrosion cracking, low yield strength and they cannot be strengthened other than by cold working, interstitial solid-solution strengthening, or precipitation hardening [51].

2.10.7  **Ferrite-Cementite**

Ferrite-cementite is a spheroidized microstructure (Figure 2-29) formed when the plain carbon steels were heated to temperatures just below the lower critical temperatures. The microstructure before spheroidization is pearlite; while during the spheroidization, the cementite lamellae of the pearlite must change their morphology to form spheroids. This process is controlled by the diffusion of carbon; and portions of the lamellae must dissolve – and then diffuse to form a spheroid from the remaining portions of lamellae. Fully spheroidized structures possess improved machinability properties [51].

![Figure 2-29: Microstructure of fully spheroidized steel. 4% picral etch. 100x. [51]](image)
2.10.8 Ferrite-Martensite

Ferrite-martensite also called dual-phased (DP) steels which refers to a class of high strength steels composing of two phases (ferritic matrix and a dispersed martensite). DP steels consists of a microstructure of about 15-20% martensite in a matrix of ferrite. The dual-phase steels do not exhibit a yield point. [51]

![Figure 2-30: Microstructure of typical dual-phased steel. 2% nital etch. 250x. [51]](image)

2.10.9 Ferrite-Austenite

Duplex-stainless steels have approximately equal proportions of austenite and ferrite. The microstructure of the ferrite-austenite steel is shown in Figure 2-31. The duplex structure has an improved stress-corrosion resistance compared to austenitic stainless steels, and improved toughness and ductility compared to ferritic stainless steels, this is due to the equal proportion of both austenite and ferrite microstructure [51].

![Figure 2-31: Microstructure of a typical mill-annealed duplex stainless steel plate, showing elongated austenite islands in the ferrite matrix. Etched in 15mL HCL in 100mL ethyl alcohol. 200x. [51]](image)
2.10.10 Graphite

Graphite is said to be formed when the carbon contents of iron-carbon alloys exceed about 2%, resulting in the formation of a graphite flake-like microstructure, as in Figure 2-32. Graphite flakes have good machinability and they also provide excellent damping capacity. [51]

![Graphite Flakes](image1)

**Figure 2-32: Classification of different graphite-flake morphologies. [51]**

2.10.11 Cementite

Cementite is a major microstructural constituent in white cast iron, shown in Figure 2-33. The cementite is formed by a eutectic reaction of liquid, forming cementite and austenite during solidification. The eutectic constituent in white cast iron is called ledeburite, which has a two-phased morphology [51].

![Cementite Microstructure](image2)

**Figure 2-33: Microstructure of a typical white cast iron. 4% picral etch. 100x. [51]**
2.11 Welding material characterizations of 3Cr12 Stainless steel

A study was done by Gooch and Davey [30] comparing the suitability of different austenitic type AISI 309L, 309 and 310 filler metals for welding 3CR12. The study showed that all consumables gave crack-free welds with matched parent metal strength, adequate bend ductility and matched cross-weld tensile properties. Type AISI 309 was recommended, due to its significant capacity for dilution without forming a crack-sensitive microstructure. The E3CR12 filler metal is not recommended for welding 3CR12 because of its detrimental effect on the fusion line-notch fracture toughness of welds.

A study was done by Grobler [31] on the weldability of 12% and 14% chromium steels. It was concluded that although a 309L weld metal on 3CR12 greatly enhances the fusion line-fracture toughness, the very low fracture of HT HAZ is evident. A type AISI 309L weld metal is recommended for welding 3Cr12 plate, especially for high integrity structural applications. It was therefore concluded that types like E3CR12 and AISI 308L filler metals are not recommended for welding 3CR12 for any structural-type applications. Neither the E3CR12 nor 309L filler metals met both the mechanical (fusion line notch fracture) and electrochemical requirements, as a filler metal for welding 3CR12.

The maximum dilution should be limited when welding 3CR12 with a type AISI 316L weld metal. The reliability and integrity of as-welded 3CR12 structures welded with even a 309L filler metal is questioned due to the very low fracture toughness of the HTHAZ adjacent to the fusion line. The HTHAZ fracture toughness of 3CR12 is not superior to that of the ferritic stainless steel AISI 409, from which 3CR12 was developed.

The effects of heat treatment on 3CR12 and AISI 316 stainless steels were studied by Akinlabi and Akinlabi [23]. The effects of heat treatment were presented by using two different cooling media (air and water). The microstructural evaluation revealed that heat-treating 3CR12 results in a dual-phase microstructure (Figure 2-34 (d) and (f)) of martensite and ferrite. AISI 316 retained its austenitic phase (Figure 2-34 (c) and (e)) throughout the heat treatment – due to the transformation occurring below 1200°C for austenitic steels while; at transformation temperatures above 1200°C the steel remains unchanged. Heat treatment of AISI 316 and 3CR12 quenched by water resulted in higher hardness values compared to the parent materials as shown in Figure 2-35 and Figure 2-36 respectively. Furthermore, the air-cooled AISI 316 resulted in higher hardness values. The water-cooled samples demonstrated
a higher HV value compared to the air-cooled samples. The grain sizes and percentage reduction showed that heat treatment alters the grain size of both 3CR12 and AISI 316. It was concluded that the difference in the cooling media appear to have a dramatic effect on the microstructure and the microhardness of stainless steels. The faster the steel was cooled, the harder it became; and also more grain size was reduced, thereby influencing the strength and the integrity of the heat-treated samples.

Figure 2-34: Microstructure of (a) As-received AISI 316, (b) As-received 3CR12, (c) Heat treated and water quenched AISI 316, (d) Heat treated and water quenched 3CR12, (e) Heat treated air cooled AISI 316 and (f) Heat treated air cooled 3CR12
The microstructure and mechanical properties of friction-stir welded AISI 409M ferritic stainless steel joints were investigated by Lakshminarayanan and Balasubramanian [24]. It was discovered that the coarse ferrite grain-based material are changed to the very fine duplex structure of ferrite and martensite, due to the rapid cooling rate and the high strain induced by severe plastic deformation caused by the frictional stirring. The tensile strength of the weld metal was found to be 57% higher than that of the base material, due to the very fine duplex ferritic martensitic structure of the weld metal caused by the friction stirring. The hardness of the stir zone ranged from 320 to 382 HV higher than that of the base metal with 170 HV.

The influence of microstructural parameters on the yield strength and the fracture toughness of 3CR12 steel was studied by Blum et al. [25]. Their study revealed that the yield strength of the dual phase 3CR12 steel in the heat-treated state was considerably higher than that of the
as-received condition. The increase in yield strength was attributed to changes in the microstructure that led to the different constraint effects in which the ferrite phase deforms. The fracture toughness values at different strain rates were higher for the as-received condition than for the heat-treated state. The more continuous martensite phase in the heat-treated 3CR12 steel imposes higher constraints on the plastic deformation of the ferrite, resulting in a decrease in the resistance to crack extension. The fracture surface morphologies were found to be consistent with the results obtained from three-point bend and impact fracture-toughness tests.

An investigation into the effect of weld-induced stresses on the structural behaviour of built-up 3CR12 columns was done by Klopper [26]. The investigation revealed that the built-up 3CR12 sections can be successfully fabricated with conventional welding techniques; if proper care is taken to the heat input and distortion. This investigation was performed using the neutron-diffraction technique to determine the typical residual stress profile associated with manual arc and laser-welded built-up 3CR12 sections. The residual stresses were then evaluated showing that both these welding techniques may be used to fabricate the structural sections. The maximum residual stresses during manual metal-arc welding are 2.85 times larger than the maximum residual stresses generated during laser welding – to achieve complete penetration. Laser welding induces smaller compressive residual stresses in the flange-end regions compared to the MMA welding.

An investigation was done by Villaret et al. [27] on the influence of the filler-wire composition on the weld microstructure of a 444 ferritic stainless steel grade. Seven metal-cored filler wires (containing 0.1%Ti, 0.45%Ti, 0.1%Ti and 0.5%Nb, 0.1% and 0.8%Nb, 0.2%Ti, 0.1%Ti and 0.4%Nb, and 0.3%Ti and 0.3%Nb) were developed for the GMAW welding of a 444 ferritic stainless steel with 19% Cr, 1.9% Mo and various Nb and Ti contents. Niobium was added to improve the high temperature mechanical properties; but it did not have any effect on the shape and grain structure of the fusion zone. Titanium has increased the wetting angle, promoted the columnar to equiaxed grain transition (CET) in the fusion zone as shown in Figure 2-37; and improved the penetration of the weld pool. It was also concluded that the filler wire with 0.3%Ti and 0.3%Nb was most suitable for welding a 444 ferritic stainless steel grade.
A research was done by Zaayman and Van Rooyen [28] on the toughness of the HAZ of welds in 11.5% Cr steels. Charpy impact properties of the welded specimens were determined at different peak temperatures; and the specimens were subjected to higher peak temperatures, resulting in an increase in the ductile-to-brittle transition temperature (DBTT) of each alloy. It was found that small amounts of ferrite are detrimental to the impact properties; the impact properties of the HTHAZ in a ferritic stainless steel are inferior to those of the base material. The study showed that it is possible to produce low carbon 11.5% Cr steel with acceptable toughness in the HAZ after welding, provided close control is exercised over the composition.

A study was done by Gooch and Ginn [29] on the HAZ zone toughness of SMA welded 12% Cr martensitic-ferritic steels. The effects, which varying welding parameters have on HAZ toughness were determined. The study was done on two steels (12mm thickness) with different ferrite factors welded by the shielded metal-arc process. Charpy impact-toughness tests revealed that increasing the arc energy over the range of 0.5 to 2.0kJ/mm caused some increase in ferrite grain size. The martensite content in the coarse-grained HAZ was determined mainly by the steel composition and the initial high-temperature thermal cycle. Reheating into the austenite range slightly increased the final martensite level in the low-ferrite-factor steel; but preheating to retard the cooling had a negligible effect. HAZ toughness was dependent mainly on the peak ferrite-grain size produced by welding. The ferrite was the major HAZ phase, thus increasing the martensite had a slightly detrimental effect on toughness; but it is expected that higher toughness would be obtained in steels with martensitic HAZ.

A study was done on the hybrid (plasma + gas tungsten arc) weldability of modified 12% Cr ferritic stainless steel by Taban et al. [32]. This study was performed on the hybrid-welding properties of 12mm thick modified 12% ferritic stainless steel, complying with EN 14003 and
UNS S41003 steels with a carbon content of 0.01% to improve the weldability. Austenitic stainless steel consumables 309L and 316LSi were used. The joints were subjected to tensile and bend test, as well as Charpy-impact toughness testing at -20°C, 0°C, and 20°C. Tensile and bend testing for hybrid welding revealed sound weld joints on the modified 12%Cr stainless steel. 309 consumable provided better mean HAZ toughness values than 316 consumable as shown in Figure 2-40; but 316 type consumables provided better mean HAZ toughness data for the joints at -20°C. In microstructural examination results shown in Figure 2-38 and Figure 2-39, some grain coarsening was determined mainly at the HTHAZs; and fused metal at the root-weld metal produced by the plasma-arc welding without filler metal. Coarse ferrite grains seemed to have no adverse effect on tensile, nor on bend properties; but they lead to relatively low impact toughness only for sub-zero temperature, depending on the amount of grain-coarsened microstructures.

![Micrographs of 12mm thick hybrid (PA+GTA) weld with 309 type of filler metal (l.9) (a) BM 200x, (b) root WM by PAW without filler metal 200x, (c) filler pass WM by GTAW with 309 type of filler metal 200x, (d) root HAZ 50x, (e) face HAZ 50x and (f) face HAZ 200x.](image-url)
A study was done by Dundu and van Tonder [33] to investigate the local buckling strength of stainless steel beams, subjected to a stress gradient. AISI type 304, 410 and type 3CR12 stainless steels were used in this study. The investigation revealed that the material properties
depend on the direction of the loading (tension or compression) type of alloy. Type 304 stainless steel exhibited more ductility (elongation of 76mm) compared to ferritic alloys type 430 and 3CR12, which had an elongation of only about 66mm. The austenitic type 304 alloy produced a more pronounced non-linear behaviour than the ferritic type 430 and 3CR12 specimens because of the lower yield strength compared with other types of steel. It was concluded from this study that an acceptable prediction of the local buckling strength of slender stainless steel webs, subjected to a stress gradient, can be obtained by using the effective design-width approach, without any plasticity-reduction factor. This study was excessively conservative for low and intermediate web slenderness.

A study was done by Topic et al. [34] on the effect of cold work and heat treatment on the fatigue behaviour of 3CR12 corrosion-resistant steel wire. The fatigue behaviour of 3CR12 corrosion-resistant steel wires was investigated as a function of the combined effects of heat treatment, such as annealing, quenching, as well as mechanical treatments, such as cold forming. The samples were heat-treated, cold-drawn and subjected to fatigue-testing under load-control mode. The study showed an increase in mechanical properties of 3CR12 steel with increasing drawing strain as shown in Table 2-18. Drawing strain increases the fatigue limit of initially annealed 3CR12 steel wire from 130 to 380 and 325MPa for smooth and notched samples, respectively. The application of cold-drawn 3CR12 steel wires is limited to low stress-fatigue conditions. The drawing of quenched 3CR12 steel was significantly improved and easier to achieve in comparison to the drawing of 3CR12 steel with an initial annealed microstructure. Quenching and successive drawing improved the fatigue strength to approximately 480 MPa. A dual-phase microstructure shown in Figure 2-41 showed a significant benefit in terms of fatigue behaviour; it delayed crack initiation and retarded the fatigue-crack propagation. Dramatic change in the fatigue-fracture mode, from transgranular to brittle, was found to be a major limiting factor for the application of quenched-drawn 3CR12 steel wires under cyclic stresses higher than 15% above the fatigue limit.
Figure 2-41: Micrographs of (a) hot rolled reinforcing bar material, (b) annealed 3CR12 steel, (c) cross section of the annealed and drawn 3CR12 steel wire and (d) quenched and drawn 3CR12 steel wire at cross section

Table 2-18: Mechanical properties of 3CR12 corrosion-resistant steel wire

<table>
<thead>
<tr>
<th>3CR12 Steel (Corrosion resistant)</th>
<th>UTS (MPa)</th>
<th>Yield (MPa)</th>
<th>Elongation (%)</th>
<th>Hardness HV₅₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annealed</td>
<td>442</td>
<td>250</td>
<td>35</td>
<td>150</td>
</tr>
<tr>
<td>Drawn-0.09 Strain</td>
<td>516</td>
<td>469</td>
<td>12.3</td>
<td>183</td>
</tr>
<tr>
<td>Drawn-0.37 Strain</td>
<td>635</td>
<td>603</td>
<td>8.96</td>
<td>220</td>
</tr>
<tr>
<td>Drawn-0.47 Strain</td>
<td>647</td>
<td>607</td>
<td>8.2</td>
<td>254</td>
</tr>
<tr>
<td>Drawn-0.68 Strain</td>
<td>738</td>
<td>667</td>
<td>8.0</td>
<td>246</td>
</tr>
<tr>
<td>Quenched</td>
<td>765</td>
<td>700</td>
<td>12.5</td>
<td>246</td>
</tr>
<tr>
<td>Quenched-0.09 Strain</td>
<td>950</td>
<td>925</td>
<td>1.7</td>
<td>310</td>
</tr>
<tr>
<td>Quenched-0.37 Strain</td>
<td>1030</td>
<td>965</td>
<td>1.5</td>
<td>340</td>
</tr>
<tr>
<td>Quenched-0.47 Strain</td>
<td>1070</td>
<td>990</td>
<td>1.4</td>
<td>393</td>
</tr>
<tr>
<td>Quenched-0.68 Strain</td>
<td>1100</td>
<td>1045</td>
<td>1.2</td>
<td>398</td>
</tr>
</tbody>
</table>

An investigation was done on the strength of stainless steel built-up sectioned columns by Bredenkamp and van der Berg [35]. The stainless steel used in this study was a modified AISI Type 409 stainless steel designated 3CR12, a corrosion-resisting steel. Due to the gradual yielding properties of Type 3CR12 corrosion-resisting stainless steel, column strength is best predicted by using the tangent modulus approach. The influence of residual stresses on column strength can be included in the tangent-modulus formulation by using the mechanical properties of stub-column tests instead of the mechanical properties of the virgin plates. It was concluded from this study that the material non-linearity is the most important variable to be considered when predicting stainless steel built-up column strength. When initial out-of-straightness is considered in predicting stainless steel built-up column strength, using the Perry-Robertson equation, conservative values are obtained beyond a slenderness parameter $\lambda$, of approximately 1.3, resulting in an overall coefficient of variance greater than 16%.

The empirical SSRC formulation may be used when predicting stainless steel built-up column strength, although very conservative values are found throughout the slenderness range. The
tangent-modulus approach compared best with the experimental results. A better prediction of type 3CR12 corrosion-resisting steel column strength was found when the residual stresses are included in the tangent-modulus formulation by using the mechanical properties obtained from the stub columns.

The microstructural and mechanical properties of laser-arc hybrid welding joint of GH909 alloy was investigated by Liu et al. [36]. A laser-arc hybrid welding of 10mm thick low-thermal-expansion super alloy Gh909 components was carried out to obtain a joint with good performance. This investigation was conducted by using an optical microscope, a scanning-electron microscope and energy-diffraction spectrum. The study revealed that the weld appearance was mainly affected by the welding parameters and a desirable weld profile can be obtained under appropriate conditions by employing laser-MIG hybrid welding. The micrograph of the weld-cross section was presented as wineglass-shaped. MC-type carbides and eutectic phases (γ²-Laves) were produced at the grain boundaries – due to the component segregation during the welding process. The strengthening phase presented in the interior of grains and kept a coherent relationship with the matrix, which improved the mechanical properties of the weld joint. The lowest hardness value occurred in the weld centre, which indicated that it was the weakest section in the whole joint. The average tensile strength of the joints reached up to 632.90MPa, nearly 76.84% that of the base metal. The fracture mode of the joint was ductile; and the main reason for the joint failure was as a result of the occurrence of porosities produced in the weld during the welding process.

The sensitization of two 11-12% Cr type 1.4003 ferritic stainless steels – during continuous cooling after welding – was studied by Gref and Du Toit [37]. These steels are designated to transform partially to austenite in the high temperature heat-affected zone (HTHAZ) adjacent to the fusion line during cooling, with austenite subsequently transforming to martensite below the Ms temperature. The investigation was prompted by a number of in-service failures of fillet welds, attributed to stress-corrosion cracking caused by sensitization. These failures were associated with fast welding speeds and fillet-weld overlap, thereby implying that low heat inputs promote sensitization in these alloys. Two EN1.4003 steel grades, designated A (steel with lower austenite potential than B) and B (steel with higher austenite potential than A) were welded using a range of heat inputs (from 0.03kJ/mm to 0.45kJ/mm) and welding speeds (from 2.36mm/s to 33.3mm/s). Rosenthal’s heat-flow model was used to relate the heat input and the welding speed to the cooling rate; and to demonstrate the influence of the welding parameters on the martensite content of the HTHAZ.
The study revealed that welding at low heat-input levels can suppress the transformation of ferrite to austenite; as the heat-affected zone cools through the (austenite + ferrite) dual-phase region during welding. This resulted in largely ferritic high-temperature heat-affected zones. Carbon super saturation of the ferrite phase occurs in the absence of sufficient austenite during cooling, resulting in extensive carbide precipitation on the ferrite-ferrite grain boundaries. Chromium back-diffusion is prevented by rapid cooling, and the ferrite-ferrite grain boundaries are sensitized to intergranular corrosion. With an increase in heat input, cooling after welding is delayed and more austenite forms in the high-temperature heat-affected zone. Sensitization is prevented by the presence of enough austenite to eliminate continuous ferrite-ferrite grain boundaries. Due to its higher austenite potential, steel B (steel with higher austenite potential than A) contained more martensite than steel A (steel with lower austenite potential than B) in the high temperature heat-affected zone after welding at comparable heat-input levels. A sufficiently high austenite potential should be maintained in these steels to promote austenite formation during cooling.

In this respect, a reduction in carbon content, or an increase in the amount of ferrite-forming elements in EN 1.4003 type steels needs to be balanced by the addition of austenite-forming elements, such as nickel. Excessive welding speeds appear to exacerbate the sensitization during low heat-input welding. Due to the absence of grain boundary austenite/martensite, AISI 409 undergoes grain growth in the heat-affected zones of the welds. As a result, it has poor toughness, fatigue and tensile properties. The carbon and nitrogen content are kept at a minimum, in order to improve the toughness, to minimize the sensitization of the steel, and to maintain a ferritic structure. Austenitic consumables, such as 308L, 309L and 316L were recommended as filler metals to improve the toughness of the welds. It is recommended that minimum heat input be used to limit the grain growth.

A study on the microstructure and mechanical properties of electron beam-welded AISI 409M-grade ferritic stainless steel was done by Lakshminarayanan et al. [38]. Single-pass autogenous welds free of volumetric defects were produced at a welding speed of 1000 mm/min. The joints were subjected to optical microscopy, scanning electron fractography, micro-hardness, transverse and longitudinal tensile, bending and Charpy-impact toughness testing. The study revealed that the coarse ferrite grains in the base metal are changed to fine columnar dendritic grains and equiaxed axial grains of ferrite with some grain boundary lath martensite, this was because of the characteristic rapid solidification. AISI 409-grade generally conforms in composition to grade S41003, 1.4003 and 3CR12. The macrographs
have shown that the weld cross-section appeared like a ‘wine-glass shape’; and no volumetric defect was observed as shown in Figure 2-42. The base metal showed a microstructure of coarser ferrite grains of about 30µm in diameter, with randomly distributed carbides. The electron beam-weld metal consisted largely of dendritic columnar grains at the outer portion, with equiaxed axial grains in the central regions. The fusion zone showed a dendritic structure as shown in Figure 2-43. The tensile strength of the electron-beam weld metal was found to be 47% higher than the tensile strength of the base material as shown in Table 2-19; hence, the specimen fractured at the base metal. The hardness at the mid cross-section of the fusion zone ranged from 280 to 322 HV as shown in Figure 2-44, which was higher than the base material (170HV). This was mainly due to the fine solidification structure, as a result of the fast solidification. The impact toughness of 409M electron beam weld metal was slightly higher than that of the base metal; and this was due to the presence of equiaxed and columnar grains perpendicular to the crack path.

**Figure 2-42:** Macrostructure of electron beam-welded 409M ferritic stainless steel: BM (a), fusion zone (b), HTHAZ (c) and LTHAZ (d)

**Figure 2-43:** Microstructure of electron beam welded 409M ferritic stainless steel joint
Table 2-19: Tensile and impact property of EBW joints in comparison with the base metal

<table>
<thead>
<tr>
<th>Joint</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation (%)</th>
<th>Notch tensile strength (MPa)</th>
<th>Notch strength ratio (NSR)</th>
<th>Impact toughness (J)</th>
<th>Joint efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>352 (6.2)</td>
<td>556 (4.1)</td>
<td>31 (8.84)</td>
<td>662 (7.2)</td>
<td>1.24</td>
<td>24 (0.8)</td>
<td>–</td>
</tr>
<tr>
<td>EBW joint (failure in BM region)</td>
<td>390 (3.4)</td>
<td>566 (3.2)</td>
<td>34.61 (1.1)</td>
<td>842 (6.8)</td>
<td>1.48</td>
<td>36 (0.7)</td>
<td>31 (1.2) 106</td>
</tr>
<tr>
<td>EBW (all weld)</td>
<td>418 (2.8)</td>
<td>790 (4.2)</td>
<td>28 (0.85)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Values given in parentheses are standard deviation of experimental results

Figure 2-44: Hardness profile of electron beam-welded 409M ferritic stainless steel joint

The structure and the properties of corrosion- and wear-resistant Cr-Mn-N steels was studied by Lenel and Knott [39]. Steels containing about 12% Cr, 10% Mn, and 0.2% N have been shown to have an unstable austenitic microstructure and to have good ductility, extreme work hardening, high fracture strength, excellent toughness, good wear resistance, and moderate corrosion resistance. A series of alloys containing 9.5 to 12.8% Cr, 5 to 10.4% Mn, 0.16 to 0.32% N, 0.05% C, and residual elements typical of stainless steels was investigated by microstructural examination and mechanical, abrasion and corrosion testing. The study showed that the microstructures ranged from martensite to unstable austenite as shown in Figure 2-45. The unstable austenitic steels transformed to α-martensite on deformation; and they displayed very high work-hardening exceeding that of Hadfield’s manganese steels.

All the experimental steels displayed very good abrasive resistance, exceeding that of the commercial abrasion resistant steels and other stainless steel. The high wear resistance is attributed to the high hardness which develops at the surface during wear as shown in Table 2-20. Corrosion resistance was similar to that of other 12% Cr steels. Properties were not much affected by minor compositional variations or rolled-in nitrogen porosity. In 12% Cr-10% Mn alloys, ingot porosity was avoided when nitrogen levels exceeded 0.14%. 
The effect of hot-rolling and annealing on the cold bulk formability of steel types 3CR12 and 304 was studied by Ulvan and Koursaris [40]. The cast structures of steel types 3CR12 and 304 were examined in this study. The study revealed that the formability that was measured in compression tests was shown to be strongly influenced by the microstructure of the alloy. The formability of the dual-phase steel 3CR12 was highest in the as-cast condition; and it decreased with increasing amounts of hot working. Annealing improved the formability of the hot-rolled material. The low formability of the worked and annealed steel 3CR12 was attributed to the development of a fibrous structure. The formability of stainless steel type 304 was lowest in the as-cast condition; because of its coarse dendritic and segregated structure. The formability of steel 304 improved with hot working; and further improvements were obtained by annealing the hot worked material. The improved formability of hot-worked steel 304 was due to the homogenization and recrystallization that took place upon hot-rolling, giving a more isotropic material. The improvements in the formability of hot-
worked steel 304 upon annealing were due to the softening and the elimination of the martensite as shown in Table 2-21. The results also showed that the microstructure of cast 3CR12 consisted of martensitic grains in a matrix of delta ferrite; the ratio of ferrite to martensite was 25:75. Coarse and fine precipitated particles of Ti (C, N) were observed as shown in Figure 2-46 (b). Coarse particles were clustered and the fine particles were mainly on the ferrite-martensite boundaries and in the ferrite phase. The microstructure of hot-rolled 3CR12 reduced by 40% of the cast structure as shown in Figure 2-46. The ferrite-to-martensite ratio was found to be 30:70. The secondary Ti (C, N) particles became coarser with increased concentration.

Figure 2-46: (a) The microstructure of steel 3CR12 as cast, (b) Primary (P) and secondary (S) particles of Ti(C,N) in as cast steel 3CR12, (c) Islands of delta ferrite matrix of austenite in as cast steel 304.
Figure 2-47: The microstructure of steel (a) 3Cr12 after hot rolling to 40% reduction, (b) 3CR12 hot rolled to 56% reduction and (c) 304 hot rolled to 29%.

Table 2-21: Data for steel 3CR12

<table>
<thead>
<tr>
<th>Condition</th>
<th>Ferrite %</th>
<th>Hardness, HV</th>
<th>Microhardness, HV</th>
<th>Formability Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>As cast</td>
<td>25</td>
<td>277</td>
<td>221</td>
<td>301</td>
</tr>
<tr>
<td>Hot rolled to 40%</td>
<td>30</td>
<td>270</td>
<td>230</td>
<td>370</td>
</tr>
<tr>
<td>Hot rolled to 50%</td>
<td>30</td>
<td>264</td>
<td>185</td>
<td>340</td>
</tr>
<tr>
<td>Hot rolled to 40% and annealed at 725°C for 23 min</td>
<td>55</td>
<td>192</td>
<td>203</td>
<td>342</td>
</tr>
<tr>
<td>Hot rolled to 50% and annealed at 725°C for 23 min</td>
<td>38</td>
<td>195</td>
<td>194</td>
<td>253</td>
</tr>
</tbody>
</table>

A study was done by Ranjbarneodeh et al. [41] on the effect of the welding parameters on the heat-affected zone of AISI409 ferritic stainless steel. The microstructural characteristics of tungsten inert-gas (TIG) welded AISI409 ferritic stainless steel were investigated by electron backscattered diffraction (EBSD), and the effects of welding parameters on the grain size, the local misorientation, and the low-angle grain boundaries were studied. It was shown in this study that higher heat input leads to larger grain sizes; thus the heat input was referred to as the decisive factor in controlling the grain size within HAZ. It was shown that the base metal and all the welded samples do not show the strong texture; and the base metal exhibited an incomplete recrystallization. It was also observed that the heat input, together with the welding speed and the current have an effect on the welding process within the HAZ.

A study was done by Mukherjee and Pal [42] on the influence of heat input on martensite formation and the impact property of ferritic-austenitic dissimilar weld metals. The study focused on the comparison of the microstructure and the mechanical properties of 409
stainless steel welds obtained by type 316L and 308L filler metals. In this study, it was found that the two major factors affecting the microstructure were the Cr\textsubscript{eq}/Ni\textsubscript{eq} ratio and the heat input. Weld metals prepared by high heat input exhibited higher toughness than those prepared by medium- and low-heat inputs wires. The type 308L specimen yielded better mechanical properties and higher amounts of martensite than did the 316L specimen.

![Figure 2-48: Optical micrographs of weld metals using 308L (a) and 316L (b) filler wires [42].](image)

308L is observed to have a higher Cr\textsubscript{eq}/Ni\textsubscript{eq} ratio, MT temperatures and relatively low SFE provide higher amount of martensite laths than 316L weld metals as shown in Figure 2-48. Weld metals prepared by high heat inputs associated with slower cooling rates generate higher amount of martensite compared to those prepared by medium and low heat input, which is probably due to the influence of MT temperatures; and hence hardenability elements.

A study was done by M. Shojaati and B. Beidokhti [43] on the characterization of AISI 304/ AISI 409 stainless steel joints using different filler materials. Weld metal type 310, 316L and 2209 were used to join the AISI 304 to AISI 409. The microstructural analysis in this study showed that the dissimilar welding led to the formation of different ferrite-austenite solidification patterns in weld metals; and no evidence of carbide/nitride phases was detected. The microstructure of 310 stainless steel weld metal was found to consist of ferrite with different morphologies in the austenitic matrix; the 310 specimen was also noted to be finer than the other specimens. The microstructure of 316L stainless steel weld metal consisted of a random arrangement of acicular ferrite in the austenite matrix. The microstructure of type 2209 weld metal was found to be a predominantly grain-boundary nucleated austenite. The
316L specimen showed the best mechanical properties from the cost-saving point of view, even though the other welds showed proper tensile strength values.

A study was done by Lakshminarayanan et al. [45] on the effects of welding processes on tensile and impact properties, hardness and the microstructure of AISI 409M ferritic stainless steel joints fabricated by duplex stainless steel filler metal. Shield metal-arc welding, gas metal-arc welding and gas tungsten-arc welding were used to weld single-pass butt welds on 4 mm rolled plates. It was found that gas tungsten-arc welded joints of ferritic stainless steel have superior tensile and impact properties compared to the shield metal-arc welding and gas metal-arc welding. This observation was mainly due to the presence of finer grains in the fusion zone and in the HAZ.

A study on the microstructure of low carbon 12% chromium stainless steel in a high temperature heat-affected zone was done by Zheng et al. [46]. The study revealed that the microstructure in HTHAZ is fully ferrite, with a small amount of martensite net probably distributed along the delta ferrite grain boundaries, if the ferrite factor (FF) is above 9.0. The martensite content increases with the decreasing ferrite factor. Heat input influences the microstructure of high FF steel in HTHAZ; the martensite content and its distribution of low FF steel are not sensitive to heat inputs; but the grain size grows with the increase of heat inputs. The coarse Ti-rich particles in low FF steels containing Ti promote intra-granular austenite formation inside delta ferrite, resulting in a packet morphology of martensite.

A study was done by Zhang et al. [47] on the microstructural evolution in the HAZ of T4003 ferritic stainless steel. An ultra-low carbon 12wt. % Cr ferritic stainless steel is modified from the 3CR12 stainless steel by an improvement of technology and chemical composition. HAZ presented on some region almost fully ferrite microstructure with irregular grain; while another region of HAZ showed martensite + ferrite dual microstructure with limited grain growth as shown in Figure 2-49, this was due to the formation of γ phase at the grain boundaries; and HAZ also exhibited the highest hardness as shown in Figure 2-50. The 3rd region in Figure 2-49(e) of the HAZ showed both martensite and ferrite structure.
The evaluation of the microstructure and the mechanical properties of laser-beam welded AISI 409M-grade ferritic stainless steel were investigated by Lakshminarayanan and Balasubramanian [44]. Single-pass autogenous welds free of volumetric defects were produced at a welding speed of 3000 mm/min. The test results revealed acceptable impact toughness and bend-strength properties; and the tensile testing indicated overmatching of the weld metal to be relative to the base metal. The weld metal region indicated higher ultimate
tensile strength (UTS) and 0.2% offset yield strength (YS), and lower elongation than the base metal.

The transverse-tensile specimen fractured in the BM region; this was due to the lowest hardness found in the BM. Flat micro-tensile specimens were used to determine all the weld metal-tensile properties. It was then concluded that the tensile strength of the fusion zone is 31% higher than the tensile strength of the base metal. The macrostructure of the laser-beam welded 409M was found to have no volumetric defect. The bend-test results showed an excellent ductility of the LBW joint; and there were no visible cracks in the cross section of the weld region. The hardness of the as-received base metal was found to be 170HV; while the fusion-zone hardness varied from 290HV to 325HV, depending on the grain size and the phases sampled by each indentation; this was mainly due to the fine solidification structure, as a result of fast solidification. The laser-beam welds solidified rapidly; as a result, coarse ferrite grains in the base metal were changed into dendritic grains. The microstructure revealed coarse ferrite grains in the base metal, largely dendritic grains at the laser-beam weld, dendritic grains at the outer portion of the LB welds; and the equiaxed axial grains were visible in the central regions.

The effect of the consumable on the properties of gas metal-arc welded EN 1.4003-type stainless steel was investigated by Taban et al. [48]. Modified 12% Cr stainless steel with very low carbon level (0.01%) was used to improve the weldability and mechanical properties; still conforming to EN 1.4003 and UNS S41003 grades were joined by gas metal-arc welding. 12mm plates were welded with ER309LSi, ER308LSi, and ER316LSi austenitic stainless steel consumables. The samples were analyzed through tensile, bend and Charpy impact toughness tests. Microstructural examinations including macro- and micrographs, grain-size analysis, hardness, and ferrite measurements were conducted. Salt spray and blister tests were also used for the corrosion testing. It was recommended from the results to use 309 and 316 welding wires for better-corrosion resistance compared with the 308 welding wires. 309 and 316 welding wires have also shown better impact toughness properties, related to the finer-grained microstructure as shown in Figure 2-51, Figure 2-52 and Figure 2-53. Post-weld heat treatment of the GMA weld with ER308LSi showed good improvement for toughness due to the tempering of the martensite at the coarse grained HAZ. The macrographs showed a reasonable weld profile for all the welds. It was concluded that the defect-free welds were obtained by GMAW. Grain coarsening had no negative effect on tensile and bend properties;
but the HTHAZ impact toughness may be affected, depending on the amount of grain-coarsened microstructures.

Figure 2-51: Photomicrographs of GMA weld with 309 filler metal (B9). A—BM, 200x; B—WM+HAZ, 50x; C—HAZ, 200x; D—WM, 200x.

Figure 2-52: Photomicrographs of GMA weld with 308 filler metal (B8). A—WM+HAZ, 50x; B—HTHAZ, 200x; C—HAZ, 200x; D—WM, 200x.
2.12 Summary

The literature review based on this study has been presented in this chapter. This chapter included the introduction, the welding processes, stainless steel and its weldability and heat treatment, the development of 3CR12 and its weldability and welding consumables, and the previous studies done on 3CR12. The previous studies were performed more on investigating AISI 409, EN 1.4003, S41003 and T4003, which are equivalent in composition to 3CR12. The Laser-welding process was dominant in the welding of 3CR12.

It was observed from the work done that:

- 309L was recommended for welding 3CR12, due to its significant capacity for dilution without forming crack-sensitive microstructure; E3CR12 and 308L filler metals were not recommended for the welding of 3CR12 for high integrity structural applications.

- The grain sizes and the percentage reduction showed that heat treatment alters the grain sizes of both 3CR12 and AISI 316. The reduction in grain size influences the strength and integrity of the heat-treated samples.

- The increase in the yield strength was related to the changes in the microstructure where ferrite phase deforms.
The impact properties of the HTHAZ in a ferritic stainless steel are similar to those of the base metal; since small amounts of ferrite are detrimental to the impact properties on 11.5% chromium stainless steel.

Higher toughness would be obtained in steels with martensitic HAZ.

309 consumable provided better mean HAZ toughness values compared to 316 consumable in hybrid welding of modified 12 & Cr stainless steel. Sound welds were revealed by tensile and bend-testing. Coarse ferrite grains at the HAZ showed not to have an adverse effect on the tensile strength, nor on the bend properties.

The grain coarsening at the HTHAZ of modified 12% Cr ferritic stainless steel had no adverse effect on the tensile and bending properties. The impact toughness of the WM and HTHAZ depends on the amount of grain-coarsened microstructures. Fine-grained microstructures can be identified by high grain size numbers; while coarse grain microstructures are identified by small grain size numbers. Maximum hardness was experienced at the HAZ; while the minimum hardness was experienced at the BM.

Austenitic consumables, such as 308L, 309L and 316L were recommended as filler metals to improve the toughness of the welds. Minimum heat input is recommended to limit grain growth. AISI 409 experienced grain growth in the HAZ of welds, due to the absence of grain-boundary austenite/martensite.

The electron-beam weld cross section appeared like a wine-glass shape, with no volumetric defects visible. The electron-beam weld metal consisted largely of dendritic columnar grains at the outer portion, with equiaxed axial grains in the central regions; and the fusion zone showed a dendritic structure. The ultimate tensile strength and hardness of the weld metal were higher than those of the base metal; hence the specimen fractured at the base metal.

The heat input was regarded as the decisive factor in controlling the grain size within the HAZ. Higher heat input should lead to a larger grain size. The heat input, welding speed and the current have an effect on the welding process within the HAZ.

Filler metal type 308L yielded better mechanical properties and a higher amount of martensite than the 316L filler metal during the welding of AISI 409.
• Filler metal 316L showed the best mechanical properties from the cost-saving point of view – even though the other welds showed proper tensile strength values during the welding of 304 to AISI 409.

• Gas tungsten arc-welded joints of ferritic stainless steel (409) have superior tensile and impact properties compared to those of shield-metal arc welding; and this was due to the presence of finer grains in the fusion zone and the HAZ.

• Microstructure in HTHAZ is fully ferrite, together with small amounts of martensite; while the martensite content increases with the decreasing ferrite factor (FF) in welding of 12% chromium steel. The grain size increases with an increase in heat input.

• HAZ presented almost fully ferrite microstructure with irregular grains in the welding of T4003; while the other region of the HAZ showed martensite + ferrite microstructure, with a limited grain growth – due to the formation of γ phase at grain boundaries; and it also exhibited the highest hardness. The 3rd region of HAZ showed both martensite and ferrite structure.

• The Laser-beam weld joint of AISI 409M produced welds free of volumetric defects. The laser beam welds’ coarse ferrite grains changed into dendritic grains in the base metal, due to its rapid solidification. The fusion zone has higher hardness than the base metal, due to the fast solidification that occurs. The transverse tensile specimen fractured at the base metal, due to the low hardness found in the BM. The higher ultimate tensile strength and the 0.2% offset yield strength and lower elongation were noticed in the weld-metal region than in the base metal.

• Welding wires 309 and 316 were recommended for gas metal-arc welding of EN 1.4003 for better corrosion resistance compared to 308 welding wire. A weld profile was produced for all the welds. Grain coarsening has no negative effect on tensile and bend properties; however the HTHAZ impact toughness may be affected, depending on the amount of grain-coarsened microstructures.

In most cases, the comparison of different filler metals was done on the AISI 409 steel; and the comparison on 3CR12 has not been completely examined. In this work, the optimum welding material of 3CR12 stainless steel will be determined. The microstructural analysis,
tensile strength, yield strength, and hardness are discussed, together with experimental measurements to optimize the welding material for 3CR12.
3 The Research Methodology

3.1 Introduction

In this chapter, the aim of the experiment, the materials, the fabrication of the testing samples and the detailed experimental methods employed are discussed. The analysis of the methods and the testing standards used are presented. These include the welding, cutting and machining of 3CR12, the parameters used and the safety precautions taken. The material characterizations employed are also discussed.

3.2 Aim of the Experiment

The aim of this experiment was to determine the optimum welding material of 3CR12; this was achieved by performing microstructural analysis, tensile testing and the hardness testing of the welded samples with different filler materials.

3.3 Material Description

A 2mm 3CR12L was used as a base material in this experiment. The 1.6mm filler metals (308L, 309L and 316L) were used to separately weld the 3CR12L material together. The gas used during the welding was Argon Industrial. The 3CR12 sample plate is shown in Figure 3-1, the chemical composition of the material is stipulated in Table A-5.

![3CR12 Test sheet](image-url)
3.4 Sample preparations

3.4.1 Experimental Matrix

The experimental matrix for this study is presented in Table 3-1 to Table 3-3. A total of 12 samples with a thickness of 2mm were used. Filler materials with a thickness of 1.6mm from each type E309L, E308L and E316L were used.

<table>
<thead>
<tr>
<th>Table 3-1: Experimental Matrix with 309L Filler Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filler Metals: 309L</td>
</tr>
<tr>
<td>Microstructure</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Hardness</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Tensile</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3-2: Experimental Matrix with 308L Filler Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filler Metals: 308L</td>
</tr>
<tr>
<td>Microstructure</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Hardness</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Tensile</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3-3: Experimental Matrix with 316L Filler Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filler Metals: 316L</td>
</tr>
<tr>
<td>Microstructure</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Hardness</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Tensile</td>
</tr>
</tbody>
</table>

3.4.2 Welding

The Tungsten Inert-Gas (TIG) Welding was done at the School of Engineering at Transnet in Pretoria. The 3CR12L plates were welded on the TIG welding machine, as shown in Figure
3-2. The 3CR12L samples were welded using three kinds of filler rods, namely: 308L, 309L and 316L.

![Figure 3-2: TIG welding Set-up](image)

The Procedure Qualification Record (PQR) in Table A-1 and Table A-2, together with the Welding-Procedure Specifications (WPS) in Table A-3 detail the parameters used for welding the 3CR12L with filler rod 308L, 309L and 316L, separately. Figure 3-3 shows the welded samples of 3CR12L welded with different filler rods.

![Figure 3-3: Welded Plates](image)
3.4.3 Welded Plate Cut Layout

The samples were prepared for cutting and machining to the required specifications upon welding. On the welded plates, a 15mm strip of material was removed from both ends of the welded plate and discarded. Then the cutting of five 20mm samples was done for tensile testing (x3) and one sample was extracted for both the microstructure and the hardness test. Material cutout profile is shown on Figure 3-4 and the detailed profile is attached in Figure A-1.

![Welded Sample Lay-out](image)

Figure 3-4: Welded Sample Lay-out

3.4.4 Tensile Test Sample

The cut samples were further machined into the tensile-testing specimens, using a milling machine. The tensile test specimens were machined to the shape and the dimensions shown in Figure 3-5, following the ASTM E8/E8M – 15a standard [58].

![Tensile Test Sample](image)

Figure 3-5: Tensile Test Sample
3.4.5 Microstructure Sample Preparation

3.4.5.1 Machining
The samples were further cut into smaller pieces in a cut-off machine, as shown in Figure 3-6 for the microstructure and hardness testing.

![Cut-off Machine](image)

3.4.5.2 Hot mounting
Further preparations for the microstructure samples were done by moulding the welded pieces for better handling during microstructure and hardness testing. Polyfast was used as the resin for hot mounting. The cut piece was placed inside the mounting machine, as shown in Figure 3-7; and it was covered with the resin (polyfast) powder; and the machine was then closed and started. The mounting was done at 180°C and 30MPa. It was heated for 4.5min and the cooling time was 2.5min; thus the total time for mounting was 7min. Figure 3-8 and Figure 3-9 show the mounted samples.
Figure 3-7: Hot Mounting Machine

Figure 3-8: Mounted Sample (Parent)
3.4.5.3 Grinding

The mounted samples were cleaned and prepared for microstructure by using the Struers polishing machine and grinding papers grade 220, 800 and 1200, as shown in Figure 3-10. The grinding was done following the steps in Table 3-4.

<table>
<thead>
<tr>
<th></th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterproof Silicon Paper</td>
<td>P#220</td>
<td>P#800</td>
<td>P#1200</td>
</tr>
<tr>
<td>Lubricant</td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
</tr>
<tr>
<td>RPM</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Load (N)</td>
<td>30</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Time (min)</td>
<td>Until plane</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
3.4.5.4 Polishing

The mounted samples were further cleaned on the polishing machine, as shown in Figure 3-10; and the steps presented in Table 3-5 were followed during this process. Self-lubricating monocry stalline (DiaMaxx Mono 3µm) was used for the 1st phase of the polishing. Colloidal silica 50nm alkaline was used for the final polishing with antidying agent [54].

Table 3-5: Stainless Steel Polishing Guideline [54]
3.4.5.5 Etching

The samples were etched using the etchant for the austenitic stainless (V2A etchant: 100ml \( \text{H}_2\text{O} \), 100ml \( \text{H}_2\text{SO}_4 \) and 10ml \( \text{HNO}_3 \)) as the 3C12 was welded with austenitic stainless steel consumables. The samples were then ready for microstructural analysis and hardness testing.

3.5 Testing

The different tests performed in this experiment are discussed in this section.

3.5.1 Macrostructure

The macrostructures of the specimens were captured using Olympus GX71 optical microscope shown in Figure 3-11.

![Figure 3-11: Olympus GX71 Optical Microscope](image)

3.5.2 Microstructure

The microstructures of the samples were analyzed using the Olympus GX71 optical microscope, shown in Figure 3-11. The results are presented in Chapter 4. Furthermore, the samples were remounted, grinded, polished, etched and analyzed further – on an Olympus Gx71 Microscope, as shown in Figure 3-11 for clearer results of the microstructure.

3.5.3 Hardness Test
After the microscopic analysis, the samples had fine grinding and were re-polished for hardness test. The hardness test was done, according to the ASTM E384-11 standard [58]. A diamond indenter was chosen; and the indentations were done at each zone at the spacing of 0.5 mm with 15 seconds dwelling time for a 300gf. The Vickers Micro-Hardness Tester shown in Figure 3-12 was used.

![Vickers Micro-Hardness Tester](image)

3.5.4 Tensile Test

Tensile testing was carried out using the Instron 1195 tensile-testing machine, as shown in Figure 3-13. This test was carried out, according to the ASTM E8/E8M – 15a standard [59]. The specimens were welded with different filler metals, namely: 308L, 306L and 316L; and the three specimens were tested for each result.
3.6 Summary

The current chapter has outlined the aim of the experiment, the material description, the fabrication process and the characterization techniques employed. The parameters used for fabrication were presented; and the parameter investigated (filler rods) was varied for the different samples produced. The experimental procedure followed in this investigation was explained, as well as the equipment and testing standards used. The results from the investigation are presented in chapter 4.
4 Results and Discussion

4.1 Introduction

In this chapter, the results of the experimental tests conducted during the course of this study are presented and discussed. The trends and correlations observed are also presented. The previous Chapter 3 depicted how the metallographic representation of the welded 3CR12 was achieved – with the different parameters employed. A number of test analyses were done, in order to confirm the objectives of this study. These include: microstructural analysis, microhardness profiling and tensile testing. The cost analysis was also added to the observations. The outcomes from these investigations were related to the processing parameters – mainly that of the filler rod.

4.2 Macro-structural analysis

The macro-appearance of the cross sections of the welded 3CR12 samples produced is presented in Figure 4-1.

![Figure 4-1: Macro-appearances of the welded 3CR12 with different filler rods](image)
The macro-appearances of the welded samples differentiated on the welded sample. The middle region represents the weld, or the fusion zone, the region with crystals on both sides of the weld represents the heat-affected zone (HAZ); and the darker regions on both ends of the sample represent the parent metal. The profiles show defect-free welds; there is full penetration; the welds have fused well; and no cracks were visible from these macrostructures.

4.3 Micro-structural Analysis

The micro-structural changes that took place for the 3CR12 welded with different filler rods were observed under an optical microscope. The microstructures taken are presented in Table 4-1 to Table 4-3.

**3CR12 welded with 308L filler rod**

The different zones of the 3CR12 sample welded with 308L filler are shown in Table 4-1. Three samples of the 3CR12 welded with 308L filler rod were analyzed; the first row shows mainly the parent metal (pm) zone microstructure; the second row shows mainly the heat-affected zone (HAZ) micro-structure; third row shows the weld or fusion zone micro-structure; and lastly, the fourth row shows the macro-appearance of each sample.

The parent metal (PM) shows ferrite and pearlite microstructure. The heat-affected zone (HAZ) shows the coarse grains, as compared to the parent metal and the fusion zone; while the fusion zone has fine grains, which present the more ferritic and less pearlite. This is due to the rate at which the weld solidified. The fusion zone is observed to consist of austenite, ferrite and martensite laths; this mix mode is the microstructure of weld metal; and it is probably due to dissimilar weld joints of the austenitic filler metal and the ferritic base metal.
3CR12 welded with 309L filler rod

The different zones of the welded 3CR12 sample welded with 309L filler, are shown in Table 4-2. Three samples of the 3CR12 welded with 309L filler rod were analyzed: the first row shows mainly the parent metal (pm) zone microstructure; the second row shows mainly the heat-affected zone (HAZ) microstructure; while the third row shows the weld or fusion zone microstructure; and lastly, the fourth row shows the macro-appearance of each sample.

The parent metal (PM) shows ferrite and pearlite microstructure. The heat-affected zone (HAZ) shows the coarse grains, as compared to the parent metal and the fusion zone, the grain coarsening has showed no effect on tensile and bend properties according to [47]. The fusion zone shows the finer grains which represent the more ferritic and less pearlite. This is due to the fast rate at which the weld solidified. The fusion zone is observed to consist of austenite, ferrite and martensite laths; this mix mode microstructure of weld metal is probably
due to dissimilar weld joints of the austenitic filler metal and the ferritic base metal. Zhang et al [47] has recommended 309 filler metal for welding 3CR12 due its better corrosion resistance.

Table 4-2: Microstructure Results (309L, 200µm)

<table>
<thead>
<tr>
<th>309L Sample1</th>
<th>309L Sample2</th>
<th>309L Sample3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>PM</td>
<td>PM</td>
</tr>
<tr>
<td>HAZ</td>
<td>HAZ</td>
<td>HAZ</td>
</tr>
<tr>
<td>W</td>
<td>W</td>
<td>W</td>
</tr>
</tbody>
</table>

Sample welded with 316L filler rod

The different zones of the welded 3CR12 sample welded with 316L filler are shown in Table 4-3. Three samples of the 3CR12 welded with 308L filler rod were analyzed; the first row shows mainly the parent metal (pm) zone microstructure; the second row shows mainly the heat-affected zone (HAZ) microstructure; the third row shows the weld or fusion zone microstructure; and lastly, the fourth row shows the macro-appearance of each sample. The parent metal (pm) shows ferrite and pearlite microstructure. The heat-affected zone (HAZ) shows the coarse grains, as compared to the parent metal and the fusion zone, which represents the more ferritic and the less pearlite. Zhang et al [47] showed that the coarsening grains have no effect on tensile and bend properties of 3CR12. The fusion zone is observed to consist of austenite, ferrite and martensite laths; this mixed mode microstructure of the weld
metal is probably due to the dissimilar weld joints of the austenitic filler metal and the ferritic base metal.

Table 4-3: Microstructure Results (316L, 200µm)

<table>
<thead>
<tr>
<th>316L Sample1</th>
<th>316L Sample2</th>
<th>316L Sample3</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>200µm</td>
<td>200µm</td>
<td>200µm</td>
</tr>
<tr>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>200µm</td>
<td>200µm</td>
<td>200µm</td>
</tr>
<tr>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>200µm</td>
<td>200µm</td>
<td>200µm</td>
</tr>
</tbody>
</table>

Summary of all the welded samples

The microstructures of the samples of 3CR12 welded with 308L, 309L and 316L filler metals are presented in Table 4-4.
Table 4-5 shows three zones of the microstructure for each sample. These results show that the 309L sample was more susceptible to heat; hence, there were larger grains on the heat-affected zone (HAZ) than on the 308L and 316L samples. From Ranjbarnodeh et al [41] findings, 308L yielded better mechanical properties and higher amount of martensite. This means that the toughness of this sample would be negatively affected. Grain size does not have any effect on the tensile and bending properties of the material, this agrees with Zhang et al [47] ‘s findings. 308L and 316L filler metals were recommended for welding of 3CR12 to itself in the Atlas Specialty Metals handbook [21].
4.4 Grain Size Characterization

Grain is composed of various small crystals that are randomly distributed in a solid metal. Grain size has a measurable effect on most of the mechanical properties: hardness; yield; strength; tensile strength; fatigue strength and the impact strength all increase with decreasing grain size. The size of the individual grains in the microstructure was measured on the optical microscope. The grain size measurements are illustrated and tabulated in Figure 4-2 to Figure 4-4 and Table 4-6.
Figure 4-2: Grain sizes for 308L (HAZ)

Figure 4-3: Grain sizes for 309L (HAZ)

Figure 4-4: Grain sizes for 316L (HAZ)
Table 4-6: Grain Size Summary

<table>
<thead>
<tr>
<th>Specimen (Grain)</th>
<th>3CR12 Filler rod (308L)</th>
<th>3CR12 Filler rod (309L)</th>
<th>3Cr12 Filler rod (316L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.43</td>
<td>22.51</td>
<td>11.39</td>
</tr>
<tr>
<td>2</td>
<td>15.88</td>
<td>23.01</td>
<td>12.95</td>
</tr>
<tr>
<td>3</td>
<td>14.90</td>
<td>22.82</td>
<td>13.40</td>
</tr>
<tr>
<td>4</td>
<td>14.79</td>
<td>21.81</td>
<td>12.69</td>
</tr>
<tr>
<td>5</td>
<td>15.18</td>
<td>22.29</td>
<td>12.36</td>
</tr>
<tr>
<td>Average grain size (µm)</td>
<td>15.24</td>
<td>22.49</td>
<td>12.56</td>
</tr>
<tr>
<td>% decrease in grain size compared to parent material</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results in Table 4-6 reveal that the grains for the 309L samples are larger than those for the 308L and 316L samples; thus 309L is more susceptible to heat, which would have a negative effect on the toughness of the material. However, the grain coarsening has no effect on the tensile and bend properties [47]. The 308L sample seems to have the smallest grains, compared to the 309L and 316L samples from the images in Figure 4-2 to Figure 4-4.

4.5 Hardness

Figure 4-5 (at the weld cap) and Figure 4-6 (at the root of the weld) show the hardness values, as a function of the distance from the weld centre across the joint, together with the macro-structures of the samples. The average hardness of the 3CR12 is 173HV; the average hardness of the 308L is 325HV; 242HV for 309L; and 345HV for 316L at the weld cap. The hardness of 309L is lower than that of the 308L and the 316L welded samples. This means that the 309L sample possesses better tensile properties, as compared to the 308L and 316L. The hardness of all the samples is higher at the weld cap than at the root of the weld, meaning the weld is stronger at the weld cap than at the root. Grobler [31] has concluded that the hardness is softer at the root of the weld than weld cap.

The maximum hardness with the minimal fluctuation lies in the fusion zone; this is mainly due to the fine solidification structure. Compared to the parent metal zone, the fusion zone shows a smaller fluctuation. The HAZ contains large grains; and the hardness of its ferrite
and austenite phases differ. Thus, the fluctuation in the HAZ is greater than that of the fusion zone. As the distance from the fusion zone increases, the hardness values gradually decrease.

Figure 4-5: Hardness Results and Macro-structures for 308L, 309L & 316L (Capping)
4.6 Tensile Test

The results revealed that 3CR12 is a ductile material; as it had a large percentage of elongation before it fractured as illustrated in Figure 4-8.

Figure 4-7 shows the fractured test sample of the 3CR12 welded with 308L weld metal; while Figure 4-8 shows the stress-strain curve of the 3CR12 welded with 308L. The sample fractured on the parent metal at about 45mm from the weld joint, indicating that the parent metal is weaker than the joint. The failure at the parent metal is because the parent metal had
the lowest hardness; as this is evident from the hardness profile shown in Figure 4-5 and Figure 4-6.

The ultimate tensile strength was extracted from the raw data for three of the 308L samples: the values were found to be 495MPa, 488MPa and 491MPa for 308S1, 308S2 and 308S3,
respectively, as illustrated in Figure 4-9. These values are above the minimum tensile strength (450MPa) of 3CR12; thus the materials comply with the design conditions.

The yield strength was observed to be 357MPa, 351MPa and 359MPa for 308S1, 308S2 and 308S3, respectively, as illustrated in Figure 4-10. The observed yield strength values are complying with the designed yield strength of 350MPa for 3CR12.

The 308L samples fractured at 231MPa, 220MPa and 220MPa for 308S1, 308S2 and 308S3 respectively, as shown in Figure 4-11.
The Elastic Modulus (E) values of 3CR12 were observed as 2.6GPa, 0.3GPa and 0.8GPa for 308L, 309L and 316L, respectively, as illustrated in Figure 4-12. These values do not meet the designed elastic modulus requirements, which is 200GPa.

Figure 4-13 shows the fractured test sample of the 3CR12 welded with 309L weld metal; and Figure 4-14 shows the stress-strain curve of the 3CR12 welded with 309L. This sample also fractured on the parent metal at about 48mm from the weld joint, indicating that the parent metal was weaker than the metal of the joint. This finding is supported by the tensile strength of 3CR12 being 460MPa and that of 309 filler metal being 670MPa.
The Ultimate Tensile Strengths (UTS) for samples 309S1, 309S2 and 309S3 were found to be 481MPa, 488MPa and 483MPa, respectively, as illustrated in Figure 4-15. These values are within the design limits of Tensile Strength for 3CR12, which is 450MPa.
The yield strengths for samples 309S1, 309S2 and 309S3 were observed to be 340MPa, 346MPa and 347MPa, as illustrated in Figure 4-16. These values are more or less the designed yield strength of the 3CR12; thus the samples met the design standards.

The 3CR12 samples 309S1, 309S2 and 309S3 fractured at 207MPa, 207MPa and 229MPa, respectively, as illustrated in Figure 4-17.
The Elastic Modulus (E) values of 3CR12 were observed as 0.6GPa, 1.3GPa and 0.8GPa for 308L, 309L and 316L, respectively, as illustrated in Figure 4-18. These values do not meet the designed elastic modulus requirement, which is 200GPa.

Figure 4-19 shows fractured tested sample of the 3CR12 welded with 316L weld metal and Figure 4-20 shows the stress-strain curve of the 3CR12 welded with 316L. The samples fractured on the parent metal at about 42mm from the weld joint, indicating that the parent metal was weaker than that of the joint.
The Ultimate Tensile Strength values were observed to be 484MPa, 486MPa and 497MPa for samples 316S1, 316S2 and 316S3, respectively, as illustrated in Figure 4-21. These values are above the minimum tensile strength (450MPa); thus the samples are within the design limits.
The yield-strength values were observed to be 354MPa, 351MPa and 349MPa for samples 316S1, 316S2 and 316S3, respectively, as illustrated in Figure 4-22. These values are at the designed yield strength of 3CR12; thus they meet the design requirements for this material.

The 3CR12 samples 316S1, 316S2 and 316S3 fractured at 201MPa, 213MPa and 224MPa, respectively, as illustrated in Figure 4-23.
The Elastic Modulus (E) values of 3CR12 were observed as 1.4GPa, 1.3GPa and 2.5GPa for 316S1, 316S2 and 316S3 samples, respectively, as illustrated in Figure 4-24. These values do not meet the designed elastic modulus requirement, which is 200GPa.

Figure 4-24 shows the stress-strain curves of the 3CR12 welded with 308L, 309L and 316L. The experimental results show a similar behavior on the ultimate tensile strength of the 308L, 309L and 316L – except for one instant, where the 316L sample was gripped at a shorter length, which resulted in the material experiencing higher strains. The tensile test results show that the TIG welding of 3CR12 produces defect-free welds. Plastic deformation mainly
occurs on the base metal, implying that the strength of the welds is influenced by the TIG joint.

![Tensile Test Results (308L, 309L & 316L)](image)

Figure 4-25: Tensile Test Results (308L, 309L & 316L)

The mechanical properties of 3CR12 showed the minimum Ultimate Tensile Strength to be 450MPa. The tested samples endured an Ultimate Tensile Strength above the minimal, which was 491MPa, 484MPa and 489MPa for 308L, 309L and 316L samples, as shown in Figure 4-26; thus, the material behaviour is as expected. The Ultimate Tensile Strength of the 3CR12 welded with 308L was higher than those of the 309L and 316L samples. This means that the 308L had better tensile properties than the 309L and 316L samples.
The mechanical properties of 3CR12 showed that the yield strength is between 280 - 450MPa. The test results revealed the average yield strength for 308L, 309L and 316L samples to be 491MPa, 484MPa and 489MPa, as shown in Figure 4-27. The yield stress of the 3CR12 welded with 308L was higher than those of the 309L and the 316L samples. This means that the 308L has better yielding properties than those of 309L and 316L.

The 3CR12 sample welded with 308L filler metal fractured before 309L and 316L samples; while the 316L sample fractured last, as shown in Figure 4-28.
The mechanical properties of 3CR12 showed that the elastic modulus is 200GPa; while the results were found to be very low; and the values of 1.2 are inconclusive; as they are too low compared to the GPa, 0.9GPa and 1.7GPa for 308L, 309L and 316L samples, respectively, as illustrated in Figure 4-29. Thus, the results are deemed to be inconclusive due to the error from the machine.

4.7 Summary

The results obtained from the different characterizations that were employed were presented in this chapter. The welding material characterizations of 3CR12 were based on the
microstructural analysis, the hardness and the tensile testing. The trends and correlations observed were reported and discussed in detail. Defect-free welds were achieved. The microstructural analysis revealed the ferritic and pearlite microstructure on the base metal; coarse grains on the HAZ, as compared to the weld metal and the fusion zone. The maximum hardness was found in the fusion zone on all the welded samples. Furthermore, the weld cap was found to be harder than the root of the weld; thus the root of the weld was weaker than the cap of the weld. 308L filler rod samples yielded better Ultimate Tensile Strength and yield-strength properties than the 309L and 316L samples.
5 Conclusion and Recommendations

5.1 Introduction

This chapter presents the conclusion and some recommendations for the future work on this study. The welding material characterization of 3CR12 was analyzed in this study, and the literature review and findings were used to draw conclusions and recommend for future studies.

5.2 Conclusion

The following observations were acquired from the study:

- The macrostructure revealed defect-free welds on all the welded samples; no cracks were observed on the welds; there was full penetration; and the welds have fused well.

- The parent metal shows ferrite and pearlite microstructure; while the HAZ contains coarse grains, as compared to the BM and the fusion zone; furthermore, it has more ferritic and a less pearlite microstructure. The coarse grains are due to the higher heat input at this region. The fusion zone consists of austenite, ferrite and martensite laths; this is probably due to the dissimilar weld joints of the austenitic filler metal and the ferritic base metal.

- Filler metal 309L seemed to be more susceptible to heat input; hence the larger grain sizes present at the HAZ than on the 308L and 316L samples. This means the toughness properties of the material would be negatively affected. The 308L, 309L and 316L samples did not fracture on the weld joints during tensile testing besides some of them having the larger grains, thus it is concluded that the grain size shows no effect on the tensile properties.

- The maximum hardness was found to be in the fusion zone on all the welded samples; this is mainly due to the fine solidification structure. The hardness values for 309L sample are lower than those of the 308L and the 316L samples; thus 309L possesses better tensile properties than the 308L and the 316L samples. The hardness values of
all welded samples are higher at the weld cap than at the root of the weld; thus the root of the weld is weaker than the weld cap.

- The ultimate tensile strength (UTS) of 3CR12 welded with 308L filler rod is found to be considerably higher than those of the 309L and 316L; this means that 308L has better tensile properties than the 309L and the 316L samples.

- The yield strength of 3CR12 welded with 308L was found to be considerably higher than that of the 309L and 316L samples; this means that the 308L possesses better yielding properties than the 309L and the 316L samples.

- From the observations above, it is concluded that the 308L filler metal is the optimum welding material for 3CR12.

5.3 Recommendations for Future Work

The objectives for this research work were met. However, the outcome from the previous studies has shown that more future work still needs to be done to improve on what has been done thus far. The following avenues were recommended:

- An effective etchant to etch the ferritic stainless steel and the austenitic stainless steel should be established for more reliable microstructural results; as the etchants used were more favorable to the parent material than the weld metal.

- Micro-tensile analysis should be included to analyze the tensile strength of the weld metal; as the sample fractured at the base metal.

- The Charpy impact test should be conducted on thicker 3CR12 samples to optimize the filler metals further. The 2mm thickness sample used in this study did not meet the minimum requirements for the impact test.

- SEM should be performed on each sample to analyze the composition of the welded samples; so that it could be linked to the microstructure and the hardness of the material.
References

10. “Stainless Steel Electrodes.” Afro E3Cr12 Product Data Sheet, Afrox. South Africa
15. “Welding Methods of Stainless Steel Pipes”. Internet: [2011]
16. “Flux cored-arc welding”. Internet: [2014]
17. “Submerged arc welding”. Internet: [2018]
   https://www.slideshare.net/Lahiru_Dilshan/submerged-arc-welding-91957274?qid=7456d091-dbf9-48c8-b865-2853d8fa7655&v=&b=&from_search=1
18. “Laser beam welding”, Internet: [2014]
   https://www.slideshare.net/antwinkoshy/laser-beam-welding-43010843?qid=73ced7c4-b115-4529-beb7-96dc86f5d6&v=&b=&from_search=2


38. A.K. Lakshminarayanan, V. Balasubramanian and G. Madhusudhan Reddy. “Microstructure and mechanical properties of electron beam-welded AISI 409M-


49. The fundamentals of gas tungsten-arc welding: preparation, consumables, and equipment necessary for the process. Internet:
August, 1998 [Feb 19, 2001]
[Jan 25, 2014]
54. “AKA-Brief Stainless and Duplex Steel”. Version5, Akasel, Denmark, 2013
55. Defects and discontinuities – ESC defects training QA/QC. Internet: https://www.slideshare.net/VlastimirNovakovic/welding-defects-45427484 [2016]
56. Welding problems and defects – causes and remedies. Internet:
A. Appendix

Table A-1: Procedure Qualification Record (PQR) Page 1
## Table A-2: Procedure Qualification Record (PQR) Page2

**PROCEDURE QUALIFICATION RECORD (PQR)**

ACCORDING TO ASME IX (2002)

### POST-WELD HEAT TREATMENT (QW-407)

<table>
<thead>
<tr>
<th>HEAT RATE</th>
<th>COOL RATE</th>
<th>HOLD TEMP</th>
<th>MENTION</th>
<th>HOLD TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### NON-DESTRUCTIVE TESTING

- **Vesual (QW190)**: Acceptable
- **Radiograpy (QW191)**: N/A
- **Liquid Penetrant**: N/A
- **Ultrasonic Testing**: N/A

### DESTRUCTIVE TESTING

#### TENSILE TEST (QW 159)

<table>
<thead>
<tr>
<th>SPECIMEN NO</th>
<th>WIDTH (mm)</th>
<th>THICKNESS (mm)</th>
<th>ULTIMATE LOAD (KSI)</th>
<th>TENSILE (MPA)</th>
<th>TYPE OF FAILURE AND LOCATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>65-4563 A</td>
<td>18.80</td>
<td>1.55</td>
<td>17.45</td>
<td>475</td>
<td>Parent material</td>
</tr>
<tr>
<td>65-4563 A</td>
<td>18.80</td>
<td>1.53</td>
<td>17.36</td>
<td>478</td>
<td>Parent material</td>
</tr>
</tbody>
</table>

#### GUIDED BEND TEST (QW 140)

- **Results**: 
  - Root bends x 2. Acceptable when bent around 9mm former at 180 degrees.
  - Face bends x 2. Acceptable when bent around 5mm former at 180 degrees.

### TOUGHNESS TEST (QW 170) - IMPACT

<table>
<thead>
<tr>
<th>SPECIMEN NO</th>
<th>NOTCH LOCATION</th>
<th>NOTCH TYPE</th>
<th>TEST TEMP</th>
<th>IMPACT VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
<td>Shear</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>96</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Longitudinal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bend Break</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NO.BREAK</td>
</tr>
</tbody>
</table>

### FILLET WELD TEST (QW 180)

- **Result of Test**: Satisfactory
- **Metal**: Yes
- **Penetration into Parent**
- **Macro Results Satisfactory**: Yes

**OTHER TESTS**: None

**TYPE OF TEST**: N/A

**RANGE QUALIFIED (QW 451)**

- **Thickness from 2.0 mm to >4.0 mm Diameter**: >600 mm

**COMPANY**: Transwerk

**NAME**: C. Viljoen

**DATE**: 05-05-2005

[Signature]

**TUV Rheinland**

**NAME and SIGNATURE**: C. Viljoen

**DATE**: 05-05-2005
Table A-3: Welding Procedure Specification (WPS)

1. Welding procedure specification

To ASME IX (BOILER & PRESSURE VESSEL CODE & INTERNATIONAL CODE)

1.1.1  Welding process:  G.T.A.W
1.1.2  Type of joint:  Open square butt with backing
1.1.3  Parent metal:  3CR12
1.1.4  Nominal thickness:  2.0mm
1.1.5  Thickness coverage:  10% Max 4.0mm
1.1.6  Purging gas:  N/A
1.1.7  Tungsten electrode:  EWTh-2  AWS A5.12-98  ISO 13638 1.6mm 
1.1.8  Tungsten size:  1.6mm  Bevel angle 60 degrees  ∠ = 120°  bevel size 2.0mm
1.1.9  Gas cup size:  Inside diameter 6mm

WELDING CONSUMABLES

2.1.1  Filler Rod & thickness:  AWS ER 309L Bare (solid) 1.6mm
1.2  Shielding gas:  Argon industrial (Air liquid product)
1.3  Gas flow rate:  10 Liters per minute

MACHINE SETTINGS

3.1.1  Welding position:  3 G
3.1.2  Pulse mode:  Off
3.1.3  Multi or Single pass:  Single pass
3.1.4  Current type:  DCEP (Straight polarity)
3.1.5  Wıre feed speed:  Manual
3.1.6  Travel speed:  Manual
3.1.7  Volts:  22 to 38
3.1.8  Amps:  60 to 89

![Welding Joint and Sequence Preparation Diagram]

1 Frans Christian Vorster as a IVW Diplomate certify that this weld procedure specification has been completed in accordance with the appropriate requirements of: ASME IX (BOILER & PRESSURE VESSEL CODE & INTERNATIONAL CODE)


Date & Signature: [Signature]

ID No.: 7111095276085  Phone No.: 3G 387 L

[UNIVERSITY OF JOHANNESBURG]
Table A-4: List of etchants and their chemical composition [53]

<table>
<thead>
<tr>
<th>Etchant No.</th>
<th>Etchant Name</th>
<th>Composition</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nital, (2%) (ASTM E 407 designated is 74 Nital)</td>
<td>2 cc HNO₃ + 98 cc Ethyl alcohol</td>
<td>Immersion</td>
</tr>
<tr>
<td>3</td>
<td>Picral, 5% (ASTM E 407 designation is 76 Picral)</td>
<td>5 gr Picric acid + 100 cc Ethyl alcohol</td>
<td>Immersion</td>
</tr>
<tr>
<td>4</td>
<td>Oxalic acid</td>
<td>10 gr oxalic acid + 10 cc H₂O</td>
<td>Electrolytic at 200/400 Ma.</td>
</tr>
<tr>
<td>6</td>
<td>Nital, 5% (ASTM E 407 designation is 74 Nital)</td>
<td>5 cc HNO₃ + 95 cc Ethyl alcohol</td>
<td>Immersion. Do not store</td>
</tr>
<tr>
<td>7</td>
<td>HCL in alcohol</td>
<td>15 cc HCL + 100 cc Ethyl alcohol</td>
<td>Immersion</td>
</tr>
<tr>
<td>8</td>
<td>Ferric Chloride</td>
<td>5 g Ferric Chloride + 50 cc HCL + 100 cc H₂O</td>
<td>Use fresh swab. Use under hood. Do not store</td>
</tr>
<tr>
<td>9</td>
<td>Marble’s Reagent (ASTM E 407 designation is 23</td>
<td>4 g CuSO₄ + 20 cc HCL + 20 cc H₂O</td>
<td>Immersion or swab</td>
</tr>
<tr>
<td>10</td>
<td>Viella’s (ASTM E 407 designation is 80 Viella’s.</td>
<td>5 cc HCL + 2 gr Picric acid + 100 cc Ethyl alcohol</td>
<td>Immersion or swab</td>
</tr>
<tr>
<td>11</td>
<td>Aqua Regia in alcohol. (ASTM E 407 designation</td>
<td>100 cc HCL + 3 cc HNO₃ + 100 cc Ethyl alcohol</td>
<td>Immersion</td>
</tr>
<tr>
<td>12</td>
<td>Chronic acid</td>
<td>10 gr CRO₃ + H₂O</td>
<td>Electrolytic at 200/400 Ma.</td>
</tr>
<tr>
<td>13</td>
<td>2% H₂SO₄</td>
<td>2 cc H₂SO₄ + 98 cc H₂O</td>
<td>Use electrolytic. Under hood. 200/400 Ma</td>
</tr>
<tr>
<td>15</td>
<td>G</td>
<td>12 cc H₃PO₄ + 41 cc HNO₃ + 47 cc H₂SO₄</td>
<td>Use electrolytic. Under hood. 200/400 Ma</td>
</tr>
<tr>
<td>18</td>
<td>Acetic Glyceria (Mixed Acids)</td>
<td>15 cc HCL + 10 cc HNO₃ + 10 cc Acetic Acid + 2/3 Drops Glycerine</td>
<td>Use fresh. Under hood. Swab. Do not store</td>
</tr>
<tr>
<td>19</td>
<td>Waterless Kalling’s (ASTM E 407 designation is</td>
<td>5 gr CuCl₂ + 100 cc HCL + 100 cc Ethyl alcohol</td>
<td>Immersion or swab</td>
</tr>
<tr>
<td>22</td>
<td>HF + HNO₃</td>
<td>1 to 3 cc HF + 2 to 6 cc HNO₃ + 100 cc H₂O</td>
<td>Swab. Handle with care. HF causes serious burns. Use in plastic container, as HF attacks glass.</td>
</tr>
<tr>
<td>23</td>
<td>HNO₃ + H₂O</td>
<td>75 cc HNO₃ + 25 cc H₂O</td>
<td>Use under hood. Electrolytic 5 to 7 amps</td>
</tr>
<tr>
<td>26</td>
<td>Glyceria (ASTM E 407 designation is 87 Glyceria)</td>
<td>15 HCl + 10 cc Glycerol + 5 cc HNO₃</td>
<td>Use fresh. Under hood. Swab. Do not store</td>
</tr>
<tr>
<td>28</td>
<td>Ralph’s</td>
<td>100 cc H₂O + 200 cc methyl alcohol + 100 cc HCl + 2 gr CuCl₂ + 7 gr FeCl₂ + 5 cc HNO₃</td>
<td>Swab</td>
</tr>
<tr>
<td>29</td>
<td>Special #4</td>
<td>10% Sodium meta-Bisulfate in distilled water</td>
<td>Immersion</td>
</tr>
<tr>
<td>30</td>
<td>Special #5</td>
<td>20 ml HCl + 4 ml H₂O (3%)</td>
<td>Swab</td>
</tr>
</tbody>
</table>
### Table A-5: 3CR12 Chemical Composition

<table>
<thead>
<tr>
<th>Sample No</th>
<th>3CR12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Si</td>
</tr>
<tr>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>1.</td>
<td>0.0087</td>
</tr>
<tr>
<td>2.</td>
<td>0.0076</td>
</tr>
<tr>
<td>3.</td>
<td>0.0072</td>
</tr>
<tr>
<td>Ø</td>
<td>0.0078</td>
</tr>
<tr>
<td>σ</td>
<td>0.00078</td>
</tr>
<tr>
<td>Ω</td>
<td>10.00</td>
</tr>
</tbody>
</table>

| As | B | Co | N | Nb | Sn | Ti | V | W | Fe |
| %  | % | %  | % | %  | %  | %  | % | %  | %  |
| 1.  | 0.0051 | 0.0026 | 0.011 | <0.010 | 0.0061 | 0.0072 | 0.012 | 0.065 | 0.081 | 85.70 |
| 2.  | 0.0049 | 0.0025 | 0.010 | <0.010 | 0.0066 | 0.0071 | 0.012 | 0.064 | 0.090 | 85.66 |
| 3.  | 0.0049 | 0.0024 | 0.010 | <0.010 | 0.0067 | 0.0070 | 0.012 | 0.064 | 0.078 | 85.87 |
| Ø   | 0.0050 | 0.0025 | 0.010 | <0.010 | 0.0065 | 0.0071 | 0.012 | 0.064 | 0.083 | 85.74 |
| σ   | 0.00012 | 0.00010 | 0.00071 | 0.00032 | 0.00010 | 0.00071 | 0.00062 | 0.112 |       |
| Ω   | 2.400 | 4.000 | 7.100 | 4.923 | 1.408 | 1.109 | 7.470 | 0.131 |       |
Figure A-1: Welded Sample Lay-out
Figure A-2: Tensile Specimen Detailed Drawing

Figure A-3: Ultimate Tensile Strength for 308L, 309L & 316L Samples
Figure A-4: Yield Strength for 308L, 309L & 316L Samples

Figure A-5: Stress at Fracture for 308L, 309L & 316L Samples
Figure A-6: Elastic Modulus for 308L, 309L & 316L Samples

Figure A-7: Hardness Test Results at the Root of the Weld (308L)
Figure A-8: Hardness Test Results at the Cap of the weld (309L)

Figure A-9: Hardness Test Results at the Root of the Weld (309L)
Figure A-10: Hardness Test Results at the Cap of the Weld (309L)

Figure A-11: Hardness Test Results at the Root of the Weld (316L)
Figure A-12: Hardness Test Results at the Cap of the Weld (316L)

Figure A-13: Hardness Test Results at the Root of the Weld (308L, 309L, 316L & Parent)
Figure A-14: Hardness Test Results at the Cap of the Weld (308L, 309L, 316L & Parent)
Table A-6: Costs for Filler Rods

<table>
<thead>
<tr>
<th>Material Number</th>
<th>Material Description</th>
<th>Quantity</th>
<th>Unit</th>
<th>Unit Price</th>
<th>Line Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>W030571</td>
<td>TIG 309L, 2.4MM SKG TUBE</td>
<td>8</td>
<td>KG</td>
<td>198.86</td>
<td>1,586.88</td>
</tr>
<tr>
<td>W030570</td>
<td>TIG 309L, 1.6MM SKG TUBE</td>
<td>5</td>
<td>KG</td>
<td>341.66</td>
<td>1,708.30</td>
</tr>
<tr>
<td>W030430</td>
<td>TIG 308L, 2.0MM SKG TUBE</td>
<td>5</td>
<td>KG</td>
<td>249.33</td>
<td>1,246.65</td>
</tr>
<tr>
<td>W030410</td>
<td>TIG 308L, 2.0MM SKG TUBE</td>
<td>5</td>
<td>KG</td>
<td>249.33</td>
<td>1,246.65</td>
</tr>
<tr>
<td>W030420</td>
<td>TIG 308L, 2.0MM SKG TUBE</td>
<td>5</td>
<td>KG</td>
<td>249.33</td>
<td>1,246.65</td>
</tr>
<tr>
<td>W030550</td>
<td>TIG 309L, 1.6MM SKG TUBE</td>
<td>5</td>
<td>KG</td>
<td>179.10</td>
<td>895.50</td>
</tr>
<tr>
<td>W030560</td>
<td>TIG 309L, 1.6MM SKG TUBE</td>
<td>5</td>
<td>KG</td>
<td>211.11</td>
<td>1,055.55</td>
</tr>
</tbody>
</table>

Continued on Next Page...