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COLD-ROLLING MILL: MODELLING OF THE ROLLING PROCESS AND CHARACTERIZATION OF THE EVOLVING PROPERTIES

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I, Olaogun Olayinka, the undersigned and the author of this thesis, hereby declare that:

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- This thesis not been submitted in any form for another degree or diploma at any university, or other institution of tertiary education; and
- The information derived from the published or unpublished work of others has been appropriately acknowledged in the text, and a list of references has been given.

----------------------------------  -----------------
Signature                        Date
DEDICATION

This dissertation is dedicated to my late Dad, Joseph Ogunleye Olaogun. His memory and teachings have been an inspiration to me; and they have instilled in me a sense of commitment to reach my goal. Thank you, Dad.
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I give thanks unto the Lord God Almighty; for He is good; and his mercy endures forever. To Him who has showered His unfailing love, grace, strength, divine protection and mercy upon me – prior to, during and the completion of this doctoral dissertation, I am forever grateful. Blessed be Thy name, Oh God of all gods!

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ABSTRACT

The cold-rolling process is a complex dynamic strain-hardening mechanism that is known for its strength improvement, excellent surface finish and dimensional tolerance. Cold rolling, a metal deformation process, is characterized by forming temperatures below the recrystallization temperature of the rolled workpiece, usually metals. Cold rolling of aluminium 8015-alloy involves deformation of the alloy metal by the use of rolls achieved in cold rolling mills to produce metal sheets of a certain thickness specified by the end users for packaging, automotive, and construction/structural applications.

Previous studies have reported large amount of research achieved on aluminium and its alloys; however, extensive work has not been accomplished on the 8-series family, especially on aluminium 8015-alloy that is processed by rolling. Likewise, scholars have not comprehensively exploited the cold rolling process, particularly the thermal analysis involved in cold rolling. This has been due to the widespread assumption of its insignificant impact during the cold rolling process. In addition, the material model utilized in the finite element simulation of the metal forming processes, are often a variety of constitutive equations that are either phenomenological, or to a varying degree physically based – due to the complex behaviour of the material.

This study is industrially based, with the objective of investigating the structural integrity of the rolled aluminium 8015-alloy. The research is centred on two aspects intending to provide increased knowledge to hands-on engineers and researchers in the rolling industry. On the one hand, experimental studies on the mechanical, metallography, and electrochemical corrosion testing of hot- and cold-rolled aluminium 8015-alloy were examined by using the Instron Universal Testing machine, the Vickers micro-hardness tester, optical and scanning electron microscopes, and the Ivium potentiostat, in order to determine the effect of strain hardening on the cold-rolled aluminium 8015-alloy in comparison to the hot-rolled alloy.

On the other hand, modelling and simulation of the cold rolling process further accounts for the strong coupling of aluminium 8015-alloy strip plastic and the roll thermo-elastic deformation in the industrial cold rolling process of aluminium 8015-alloy. Two-dimensional and three-dimensional finite element models and its simulation were accomplished using MSC Marc Mentat. The thermo-mechanical behaviour of aluminium 8015-alloy during the industrial cold-rolling process was examined with a two-contact algorithm finite element simulation. The finite element simulation contributed to the deformation and thermal
behavioural analysis of the aluminium 8015-alloy and the work rolls, especially in the deformable-deformable contact algorithm during the cold-rolling process. The findings of both the experimental studies and the finite-element analysis are presented.

Firstly, the reversing and non-reversing cold-rolled aluminium 8015-alloy sheet samples entirely showed improved strengths and enhanced hardness properties, with a reduced amount of ductility compared to the hot-rolled aluminium 8015 sample. Moreover, for the non-reversing cold-rolled aluminium 8015 sheet samples of varying gauge thickness, the strengths, hardness and the amount of ductility increases with percent cold work; but it starts to decrease when the gauge thickness is ≤ 1 mm.

Secondly, the microstructural observation of the hot-rolled, reversing cold-rolled and the non-reversing cold-rolled aluminium 8015-alloy samples all showed an equiaxied grain structure. Microstructural observation of the hot-rolled aluminium 8015-alloy sample in the longitudinal and transverse section rolling direction reveals densely populated smaller grains in the transverse section, as compared with the longitudinal section. Further investigation into the microstructure of the reversing and non-reversing cold-rolled aluminium 8015-alloy sheet samples both confirms higher grain size in the longitudinal section. Moreover, the non-reversing cold-rolled aluminium 8015-alloy sheet samples with different percentages of cold work or gauge thickness were examined.

The average grain size measured in both the longitudinal and transverse sections decreases with percent cold work or gauge thickness – except for an observed increment in the average grain size of the 1 mm gauge thickness cold-worked sample. The presence of bright particles in the SEM images for the entire samples was also observed. The EDS analysis shows Manganese (Mn) atoms heterogeneously present in solid solution in the aluminium matrix.

Thirdly, electrochemical corrosion examination of the hot- and cold-rolled aluminium 8015-alloy at different surface roughness in natural seawater reveals that the surface roughness affects the corrosion resistance of both hot- and cold-rolled aluminium 8015-alloy in natural sea water. A further outcome reveals that cold-rolled aluminium 8015-alloy exhibits lower resistance to corrosion in natural sea water at varying degrees of surface roughness than the hot-rolled aluminium 8015-alloy. Moreover, the EDS elemental analysis reveals the existence of insoluble sulphate complexes formed on the surface during corrosion.

Lastly, aluminium 8015-alloy behaviour during the strain hardening process for the 2-D and 3-D finite element simulation has confirmed the neutral, or no-slip zone, in the region close to the exit point of the rolled aluminium 8015 plate/sheet. This is established in the plastic
strain rate and in the shear stress distribution in the simulated model pictures. Moreover, aluminium 8015-alloy during deformation process shows that the rate of deformation shifts from high to low in a cross-like pattern; and it diminishes towards the exit gap, particularly close to the neutral zone. This concludes that deformation takes place in a stepwise manner through the roll gap.

In addition, the effect of energy exchange, as a result of heat input to the finite element simulation in the coupled thermo-mechanical analysis shows a lower magnitude of contact frictional force, plastic strain rate and normal stress; and higher shear stress magnitude in the roll bite of the strain-hardened aluminium 8015-alloy, as compared to the two-dimensional finite element simulation without the consideration of thermal input. Validation of the predicted roll separating forces for the four pass schedules in finite element simulations has shown good correlations – except for the fourth pass schedule that deviates with a larger error margin.

Conclusively, a thorough investigation in the behavioural properties of rolled aluminium 8015-alloy has been effectively studied experimentally and in the finite-element analysis context.
# TABLE OF CONTENTS

COPYRIGHT STATEMENT .................................................................................................................. i
AUTHOR’S DECLARATION ............................................................................................................... ii
DEDICATION .................................................................................................................................. iii
ACKNOWLEDGEMENTS .................................................................................................................. iv
ABSTRACT ...................................................................................................................................... vi
TABLE OF CONTENTS .................................................................................................................... ix
LIST OF ABBREVIATIONS ............................................................................................................. xiv
NOMENCLATURE .......................................................................................................................... xv
LIST OF FIGURES .......................................................................................................................... xvi
LIST OF TABLES ............................................................................................................................. xxvi
LIST OF PUBLICATIONS ............................................................................................................... xxviii
GLOSSARY OF TERMS .................................................................................................................... xxix
CHAPTER 1 ...................................................................................................................................... 1
  1.1 Background ............................................................................................................................... 1
  1.2 Motivation ................................................................................................................................ 2
  1.3 Problem statement ................................................................................................................... 2
  1.4 Significance of the research ..................................................................................................... 3
  1.5 Research objectives .................................................................................................................. 3
  1.6 Hypothesis statement .............................................................................................................. 4
  1.7 Organisation of the thesis ........................................................................................................ 4
CHAPTER 2 ................................................................................................................................... 6
LITERATURE REVIEW ................................................................................................................... 6
  2.1 Introduction ............................................................................................................................... 6
  2.2 Background of metals and its use ............................................................................................ 6
  2.3 Aluminium and its alloys ......................................................................................................... 8
    2.3.1 Production of aluminium ................................................................................................. 8
    2.3.2 Alloying of pure aluminium .......................................................................................... 10
    2.3.3 Standard designation numbering system for wrought aluminium and aluminium alloys .................................................................................................................. 10
    2.3.4 Classification of wrought aluminium alloys ................................................................. 12
    2.3.5 Preparation of wrought aluminium alloys for rolling .................................................. 15
2.4 Corrosion of aluminium alloys ................................................................. 16
  2.4.1 Pitting corrosion ................................................................................... 18
  2.4.2 Bimetallic corrosion ............................................................................ 18
2.5 Roll forming ............................................................................................... 19
2.6 Roll-forming mills ..................................................................................... 20
  2.6.1 Classification of roll-forming mills ......................................................... 21
2.7 Cold rolling process .................................................................................. 26
2.8 Rolling-mill structure ............................................................................... 27
2.9 Model of the rolling process ..................................................................... 29
  2.9.1 Slab analysis of the rolling process ......................................................... 29
  2.9.2 Dynamic model of rolling process ......................................................... 30
  2.9.3 The hydraulic servo system ................................................................. 32
2.10 Review of the mechanics and the mathematical models of the rolling process .................................................................................. 33
  2.10.1 Geometric relations in the rolling process ............................................ 34
  2.10.2 Roll-bite condition ................................................................................ 35
  2.10.3 Neutral/ no-slip zone .......................................................................... 36
  2.10.4 Conventional models ........................................................................... 37
  2.10.5 Finite element model .......................................................................... 40
2.11 Cold-rolling mill system modelling and simulation ................................... 41
2.12 Summary ................................................................................................. 42
CHAPTER 3 ..................................................................................................... 44
THE RESEARCH METHODOLOGY .................................................................. 44
3.1 Introduction ............................................................................................... 44
3.2 Research design and approach .................................................................. 44
3.3 Research problems .................................................................................... 47
3.4 Material ..................................................................................................... 48
  3.4.1 Material preparation for elemental analysis of rolled AA8015 specimen samples ................................................................. 50
  3.4.2 Material preparation and procedure for the mechanical, tensile and hardness test experiment of rolled AA8015 specimen samples ................................................................. 51
3.4.3 Material preparation and procedure for optical metallography examination of rolled AA8015 specimen samples ............................................................... 53

3.5 Electrochemical corrosion investigation of rolled AA8015 alloy .................. 55
  3.5.1 Corrosion samples’ preparation, materials and equipment ......................... 55
  3.5.2 Electrochemical corrosion test procedure ............................................... 57

3.6 MSC Marc Mentat .......................................................................................... 58

3.7 Modelling and simulation of the industrial cold-rolling process of AA8015-alloy ... 59
  3.7.1 2-D and 3-D finite element simulation .................................................. 59
  3.7.2 Coupled thermo-mechanical 2-D finite element simulation of the cold-rolling process of AA8015-alloy ......................................................... 66

3.8 Summary ......................................................................................................... 72

CHAPTER 4 ............................................................................................................. 73

RESULTS AND DISCUSSION .................................................................................... 73

4.1 Introduction ....................................................................................................... 73

4.2 Mechanical tensile and hardness test results .................................................. 74
  4.2.1 Mechanical tensile test measurements for hot-rolled AA8015 specimen samples ............................................................................................... 74

  4.2.2 Mechanical tensile test measurements for reversing cold-rolled AA8015 specimen 1.2mm thickness samples ......................................................... 75

  4.2.3 Mechanical tensile test measurements for non-reversing cold-rolled AA8015 specimen 1mm thickness samples .................................................. 77

  4.2.4 Mechanical tensile test measurements for non-reversing cold-rolled AA8015 specimen 2mm thickness samples .................................................. 79

  4.2.5 Mechanical tensile test measurements for non-reversing cold-rolled AA8015 specimen 3mm thickness samples .................................................. 81

  4.2.6 Mechanical tensile test measurements for non-reversing cold-rolled AA8015 specimen 4mm thickness samples .................................................. 83

  4.2.7 Mechanical tensile test measurements for non-reversing cold-rolled AA8015 specimen 5mm thickness samples .................................................. 85

  4.2.8 Mechanical tensile test measurements for non-reversing cold-rolled AA8015 specimen 6mm thickness samples .................................................. 87
4.3 Microstructural analysis of rolled AA8015 specimen samples ................................. 91
  4.3.1 Microstructural observation of hot-rolled AA8015 sample .............................. 91
  4.3.2 Microstructural observation of reversing cold-rolled AA8015 sample .......... 92
  4.3.3 Microstructural observation of non-reversing cold-rolled AA8015 samples .... 94

4.4 Corrosion behaviour of hot-rolled and cold-rolled AA8015 alloy in natural sea
water ................................................................................................................................ 103
  4.4.1 Open circuit potential ($E_{oc}$) measurement .................................................. 104
  4.4.2 Polarization curve measurements .................................................................... 108
  4.4.3 Corrosion rate analysis .................................................................................... 110
  4.4.4 Visual and microstructural observation before and after electrochemical corrosion test .................................................................................................................. 117

4.5 2-D and 3-D finite element simulation results ....................................................... 127
  4.5.1 Contact friction force distribution .................................................................... 127
  4.5.2 Plastic strain rate distribution .......................................................................... 129
  4.5.3 Equivalent Von Mises Stress distribution ....................................................... 131
  4.5.4 Normal and shear stress distribution ............................................................... 134
  4.5.5 Roll separating force and roll torque ............................................................... 137
  4.5.6 Validation of roll separating force ..................................................................... 139

4.6 Coupled thermo-mechanical 2-D finite element simulation results ..................... 140
  4.6.1 Contact friction-force distribution .................................................................... 140
  4.6.2 Plastic strain rate distribution .......................................................................... 142
  4.6.3 Equivalent Von Mises stress .......................................................................... 144
  4.6.4 Normal and shear stress distribution ............................................................... 145
  4.6.5 Heat flux distribution ....................................................................................... 149
  4.6.6 Temperature distribution ............................................................................... 151
  4.6.7 Roll-separating force and roll torque ............................................................... 153
  4.6.8 Validation of roll separating force ..................................................................... 156

4.7 Summary .............................................................................................................. 156

CHAPTER 5 .................................................................................................................... 160
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK .................. 160
5.1 Introduction ........................................................................................................... 160
5.2 General conclusions ............................................................................................... 160
  5.2.1 Mechanical and metallography test ................................................................. 160
  5.2.2 Electrochemical corrosion test ......................................................................... 161
  5.2.3 2-D and 3-D Finite Element Simulation of rolling process of AA8015-alloy ... 161
  5.2.4 Coupled thermo-mechanical finite element analysis ....................................... 161
5.3 Recommendations for future work ...................................................................... 162
REFERENCES .............................................................................................................. 163
APPENDIX A .................................................................................................................. 177
APPENDIX B .................................................................................................................. 200
## LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-D</td>
<td>Two-Dimensional</td>
</tr>
<tr>
<td>3-D</td>
<td>Three-Dimensional</td>
</tr>
<tr>
<td>AA</td>
<td>Aluminium Alloy</td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standard Institute</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>BUR</td>
<td>Back-Up Roll</td>
</tr>
<tr>
<td>C. Rate</td>
<td>Corrosion Rate</td>
</tr>
<tr>
<td>CR</td>
<td>Cold Rolling</td>
</tr>
<tr>
<td>CSIR</td>
<td>Council for Scientific and Industrial Research</td>
</tr>
<tr>
<td>( E_a )</td>
<td>Anodic Potential</td>
</tr>
<tr>
<td>( E_c )</td>
<td>Cathodic Potential</td>
</tr>
<tr>
<td>( E_{corr} )</td>
<td>Corrosion Potential</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy Dispersive X-ray Spectrometry</td>
</tr>
<tr>
<td>( E_{oc} )</td>
<td>Open Circuit Potential</td>
</tr>
<tr>
<td>FCC</td>
<td>Face centred cubic</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Model</td>
</tr>
<tr>
<td>HR</td>
<td>Hot Rolling</td>
</tr>
<tr>
<td>HV</td>
<td>Vickers Hardness</td>
</tr>
<tr>
<td>( I_{corr} )</td>
<td>Corrosion Current density</td>
</tr>
<tr>
<td>OP</td>
<td>Optical Microscope</td>
</tr>
<tr>
<td>pH</td>
<td>Potential of Hydrogen</td>
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<tr>
<td>( R_p )</td>
<td>Polarization Resistance</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>TARM</td>
<td>Tower Aluminium Rolling Mill</td>
</tr>
<tr>
<td>T_m</td>
<td>Melting Temperature</td>
</tr>
<tr>
<td>UTS</td>
<td>Ultimate Tensile Strength</td>
</tr>
<tr>
<td>UTS</td>
<td>Universal Testing System</td>
</tr>
<tr>
<td>WR</td>
<td>Work Roll</td>
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NOMENCLATURE

μm  Micro-meter
A   Ampere
A/cm² Ampere per centimetre squared
Al  Aluminium
C   Carbon
Cr  Chromium
e⁻  Electron
Fe  Iron
g/cm³ grams per centimetre cubed
GPa Giga Pascal
H   Hydrogen
kg/m³ Kilogramme per metre cubed
kNm Kilo-Newton metre
kW/m² °C Kilo Watt per square metre per degree Celsius
kΩ  Kilo-ohm
Mg  Magnesium
mm/y Millimetre per year
Mn  Manganese
MN  MegaNewton
MPa Mega Pascal
mV/s Milli-Volt per second
MW/m² Mega Watt per metre squared
O   Oxygen
°C Degrees Celsius
rad/s Radians per second
Si  Silicon
Ti  Titanium
Zn  Zinc
LIST OF FIGURES

Figure 2-1: Sketch of a rolling mill by Leonardo da Vinci 1485 [60] ................................................. 7
Figure 2-2: Aluminium production process and life cycle [70] ........................................................ 10
Figure 2-3: Diagram showing anodic and cathodic current components of the corrosion process [93] .................................................................................................................................................. 17
Figure 2-4: Micrographs showing evidence of pitting corrosion in (a) AA5083 and (b) AA1100 [102] ............................................................................................................................................................................. 18
Figure 2-5: Aftermath of bimetallic corrosion on the aluminium plate along the joint with mild steel [105] .......................................................................................................................................................... 19
Figure 2-6: A typical laboratory roll-forming mill [115] ........................................................................ 21
Figure 2-7: A continuous mill with four stands [106] ......................................................................... 23
Figure 2-8: Tandem-rolling mill with two stands [116] ..................................................................... 23
Figure 2-9: Schematic diagram showing two-high mill-reversing and non-reversing types [111] ... 24
Figure 2-10: Schematic diagram of a three-high mill [111] .............................................................. 24
Figure 2-11: Schematic diagram of a four-high mill [118] ................................................................. 25
Figure 2-12: Schematic diagram of a cluster mill [111] ..................................................................... 25
Figure 2-13: Schematic diagram of a planetary mill [111] ................................................................. 26
Figure 2-14: A rolling mill structure without the auxiliary apparatus [120] ........................................ 29
Figure 2-15: Geometry of the roll gap in rolling process [125] ................................................................ 31
Figure 2-16: Schematic diagram for elastic and plastic states in the roll-bite [133] ......................... 34
Figure 2-17: Schematic diagram showing neutral or no-slip zone in the roll bite [136] ................. 37
Figure 2-18: Schematic diagram showing cross section of the deformation in the roll-bite [137] .... 38
Figure 2-19: Simple flow-chart showing the fundamental concepts of the Finite Element Method (FEM) ............................................................................................................................................... 40
Figure 3-1: Schematic illustration showing the flow-chart of the research approach presented in this study ............................................................................................................................................... 46
Figure 3-2: Rolled specimen samples from Tower Aluminium Nigeria Plc: (a) hot rolled specimen sample with 7 mm thickness [Ra = 2.50 µm]; and (b) cold rolled specimen sample with 1.2 mm thickness [Ra = 0.70 µm] .......................................................................................................................... 49
Figure 3-3: Cold-rolled specimen samples gauges after cutting for metallography and tensile test experiment: (a) 6 mm thickness; (b) 5 mm thickness; (c) 4 mm thickness; (d) 3 mm thickness; (e) 2 mm thickness; and (f) 1 mm thickness .................................................................................................................. 50
Figure 3-4: Some pictures showing square-cut AA8015 specimen samples in sizes of 60 x 60 mm^2: (a) a hot-rolled specimen sample; and (b) a cold-rolled specimen sample ........................................................................ 51
Figure 3-5: Machined tensile test specimen samples ........................................................................ 52
Figure 3-6: Experimental set-up depicting AA8015 alloy plate tensile test with Instron Model 4400

Figure 3-7: Illustration of the cut specimen shape and dimensions for microstructural examination:
(a) rectangular shape of hot-rolled AA8015 block with 7 mm thickness; (b) rectangular shape of cold-rolled AA8015 block with 1.2 mm thickness

Figure 3-8: Pictures showing the preparation of AA8015 alloy samples for electrochemical corrosion testing: (top left) square-shaped corrosion samples cut in 10 mm x 10 mm surface area; (bottom centre) Cut corrosion samples stocked with copper wire before mounting; and (top right) cold-mounted corrosion samples exposed surface area of 100 mm² after cleaning

Figure 3-9: Electrochemical experimental set-up showing an open glass polarization cell

Figure 3-10: Schematic diagrammatic representation of the rolling process, showing the roll stack (Work Roll, WR; and Back-up Roll, BUR) [178]

Figure 3-11: Geometric FE model representation of the AA8015 alloy rolling process before the start of rolling (a) Two-dimensional FE model and, (b) Three-dimensional FE model

Figure 3-12: 2-D FE model representation before the start of rolling, showing the boundary conditions on the deformable plate/sheet

Figure 3-13: 3-D FE model representation before the start of rolling, showing the boundary conditions on the deformable plate/sheet

Figure 3-14: Geometric 2-D deformable-rigid contact FE model representation of the AA8015 alloy rolling process before the start of rolling, showing a magnified entrance region

Figure 3-15: Geometric 2-D deformable-deformable contact FE model representation of the AA8015 alloy rolling process before the start of rolling showing magnified entrance region

Figure 3-16: Plasticity curves for hot- and cold- rolled AA8015-alloy specimens

Figure 3-17: 2-D coupled thermo-mechanical FE model representation for deformable-rigid contact before the start of rolling showing boundary conditions on the deformable plate/sheet

Figure 3-18: 2-D coupled thermo-mechanical FE model representation for deformable-deformable contact before the start of rolling, showing boundary conditions on the deformable plate/sheet

Figure 4-1: Stress-strain graph for the hot-rolled AA8015 specimen 7 mm thickness for sample 7_1

Figure 4-2: Stress-strain graph for the hot-rolled AA8015 specimen 7 mm thickness for sample 7_2

Figure 4-3: Stress-strain graph for the hot-rolled AA8015 specimen 7 mm thickness for sample 7_3

Figure 4-4: Stress-strain graph for reversing cold-rolled AA8015 specimen 1.2 mm thickness for sample 1.2_1
Figure 4-5: Stress-strain graph for reversing cold-rolled AA8015 specimen 1.2 mm thickness for sample 1.2_2 ............................................................................................................................. 76
Figure 4-6: Stress-strain graph for reversing cold-rolled AA8015 specimen 1.2 mm thickness for sample 1.2_3 ............................................................................................................................. 76
Figure 4-7: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 1 mm thickness for sample 1_1 ................................................................................................................................ 77
Figure 4-8: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 1 mm thickness for sample 1_2 ................................................................................................................................ 78
Figure 4-9: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 1 mm thickness for sample 1_3 ................................................................................................................................ 78
Figure 4-10: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 2 mm thickness for sample 2_1 .......................................................................................................................... 79
Figure 4-11: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 2 mm thickness for sample 2_2 .......................................................................................................................... 79
Figure 4-12: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 2 mm thickness for sample 2_3 .......................................................................................................................... 80
Figure 4-13: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 3 mm thickness for sample 3_1 ................................................................................................................................ 81
Figure 4-14: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 3 mm thickness for sample 3_2 ................................................................................................................................ 81
Figure 4-15: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 3 mm thickness for sample 3_3 ................................................................................................................................ 82
Figure 4-16: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 4 mm thickness for sample 4_1 ................................................................................................................................ 83
Figure 4-17: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 4 mm thickness for sample 4_2 ................................................................................................................................ 83
Figure 4-18: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 4 mm thickness for sample 4_3 ................................................................................................................................ 84
Figure 4-19: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 5 mm thickness for sample 5_1 ................................................................................................................................ 85
Figure 4-20: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 5 mm thickness for sample 5_2 ................................................................................................................................ 85
Figure 4-21: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 5 mm thickness for sample 5_3 ................................................................................................................................ 86
Figure 4-22: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 6mm thickness for sample 6_1 ................................................................................................................................ 87
Figure 4-23: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 6 mm thickness for sample 6_2 .................................................................................................................................................. 87

Figure 4-24: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 6 mm thickness for sample 6_3 .................................................................................................................................................. 88

Figure 4-25: Column chart showing the influence of cold work on the Hardness Values (HV) of reversing and non-reversing cold-rolled AA8015 specimen samples ......................................................... 90

Figure 4-26: Clustered column chart showing the material properties of hot-rolled and cold-rolled AA8015 alloy .............................................................................................................................................. 91

Figure 4-27: Light optical micrographs of hot-rolled AA8015 sample at 500x magnification: (a) grain structure (longitudinal section) of hot-rolled AA8015-alloy (b) grain structure (transverse section) of hot-rolled AA8015-alloy ................................................................................................................. 92

Figure 4-28: SEM images of hot-rolled AA8015 sample showing magnified grain structures: (a) grain structure (longitudinal section) of hot-rolled AA8015-alloy (b) grain structure (transverse section) of hot-rolled AA8015-alloy ................................................................................................................. 92

Figure 4-29: Light optical micrographs of reversing cold-rolled AA8015 sample at 500x magnification: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ................................................................. 93

Figure 4-30: SEM images of reversing cold-rolled AA8015 sample showing magnified grain structures: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ................................................................. 93

Figure 4-31: Light optical micrographs of non-reversing cold-rolled AA8015 sample (6 mm thickness) at 500x magnification: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ................................................................. 94

Figure 4-32: SEM images of non-reversing cold-rolled AA8015 sample (6 mm thickness) showing magnified grain structures: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ................................................................. 94

Figure 4-33: Light optical micrographs of non-reversing cold-rolled AA8015 sample (5 mm thickness) at 500x magnification: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ................................................................. 95

Figure 4-34: SEM images of non-reversing cold-rolled AA8015 sample (5 mm thickness) showing magnified grain structures: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ................................................................. 95

Figure 4-35: Light optical micrographs of non-reversing cold-rolled AA8015 sample (4 mm thickness) at 500x magnification: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ................................................................. 96
Figure 4-36: SEM images of non-reversing cold-rolled AA8015 sample (4 mm thickness) showing magnified grain structures: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ........................................... 96

Figure 4-37: Light optical micrographs of non-reversing cold-rolled AA8015 sample (3 mm thickness) at 500x magnification: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ................................. 97

Figure 4-38: SEM images of non-reversing cold-rolled AA8015 sample (3 mm thickness) showing magnified grain structures: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ................................. 97

Figure 4-39: Light optical micrographs of non-reversing cold-rolled AA8015 sample (2 mm thickness) at 500x magnification: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ................................. 98

Figure 4-40: SEM images of non-reversing cold-rolled AA8015 sample (2 mm thickness) showing magnified grain structures: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ................................. 98

Figure 4-41: Light optical micrographs of non-reversing cold-rolled AA8015 sample (1 mm thickness) at 500x magnification: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ................................. 99

Figure 4-42: SEM images of non-reversing cold-rolled AA8015 sample (1 mm thickness) showing magnified grain structures: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy ................................. 99

Figure 4-43: (a) SEM image showing bright particles of AA8015-alloy. (b-g) EDS spectra showing the elemental composition of the selected precipitates (1-6), respectively ................................. 101

Figure 4-44: EDS elemental mapping of (a) hot-rolled AA8015-alloy (b) cold-rolled AA8015-alloy ................................................................................................................................................ 102

Figure 4-45: Variation of open circuit potential with time for hot-rolled AA8015-alloy (Ra≈1.37 µm) immersed in natural sea water ........................................................................................................... 104

Figure 4-46: Variation of open circuit potential with time for hot-rolled AA8015-alloy (Ra≈0.65) immersed in natural sea water ........................................................................................................... 104

Figure 4-47: Variation of open circuit potential with time for hot-rolled AA8015-alloy (Ra≈0.19) immersed in natural sea water ........................................................................................................... 105

Figure 4-48: Variation of open circuit potential with time for hot-rolled AA8015-alloy (Ra≈0.10) immersed in natural sea water ........................................................................................................... 105

Figure 4-49: Variation of open circuit potential with time for cold-rolled AA8015-alloy (Ra≈1.54) immersed in natural sea water ........................................................................................................... 106

Figure 4-50: Variation of open circuit potential with time for cold-rolled AA8015-alloy (Ra≈0.83) immersed in natural sea water ........................................................................................................... 106
Figure 4-51: Variation of open circuit potential with time for cold-rolled AA8015-alloy (Ra≈0.18) immersed in natural sea water ................................................................. 107

Figure 4-52: Variation of open circuit potential with time for cold-rolled AA8015-alloy (Ra≈0.04) immersed in natural sea water ................................................................................................ 107

Figure 4-53: Polarization curves of hot-rolled AA8015-alloy immersed in natural sea water at (a) Ra≈1.37 µm; (b) Ra≈0.65 µm; (c) Ra≈0.19 µm; (d) Ra≈0.19 µm ........................................ 109

Figure 4-54: Polarization curves of cold-rolled AA8015-alloy immersed in natural sea water at (a) Ra≈1.54 µm; (b) Ra≈0.83 µm; (c) Ra≈0.18 µm; (d) Ra≈0.04 µm ........................................ 110

Figure 4-55: Slope analysis of hot-rolled AA8015 (Sample 1 for Ra=1.37 µm) $E_{a1} = -0.720 \, V$; $E_{c2} = -0.704 \, V$ ........................................................................................................ 111

Figure 4-56: Tafel analysis of hot-rolled AA8015 (Sample 1 for Ra=1.37 µm) $E_{a1} = -0.827 \, V$; $E_{a2} = -0.801 \, V$; $E_{c1} = -0.657 \, V$; $E_{c2} = -0.645 \, V$ ............................................................................. 111

Figure 4-57: Macrographs showing visual observation for hot- and cold-rolled AA8015 samples at Ra=1.37 and 1.54 µm respectively. (a, b) images before corrosion for hot- and cold-rolled samples respectively; (c, d) images after corrosion for hot- and cold-rolled samples respectively ............................................................................................................................. 118

Figure 4-58: Macrographs showing visual observation for hot- and cold-rolled AA8015 samples at Ra=0.65 and 0.83 µm respectively. (a, b) images before corrosion for hot- and cold-rolled samples respectively; (c, d) images after corrosion for hot- and cold-rolled samples respectively ............................................................................................................................. 118

Figure 4-59: Macrographs showing visual observation for hot- and cold-rolled AA8015 samples at Ra=0.19 and 0.18 µm respectively. (a, b) images before corrosion for hot- and cold-rolled samples respectively; (c, d) images after corrosion for hot- and cold-rolled samples respectively ............................................................................................................................. 119

Figure 4-60: Macrographs showing visual observation for hot- and cold-rolled AA8015 samples at Ra=0.10 and 0.04 µm respectively. (a,b) images after corrosion for hot-and cold-rolled samples respectively ............................................................................................................................. 119

Figure 4-61: (a) EDS elemental map before corrosion of rolled AA8015-alloy (b) Map sum spectrum of the rolled AA8015-alloy ............................................................................................................................. 120

Figure 4-62: SEM images of corroded hot-rolled AA8015 sample at Ra≈1.37 µm. (a) image before corrosion at 271-x magnification; (b-d) images after corrosion at increased magnifications. 121

Figure 4-63: SEM images of corroded hot-rolled AA8015 sample at Ra≈0.65 µm. (a) image before corrosion at 267-x magnification; (b-d) images after corrosion at increased magnifications. 121

Figure 4-64: SEM images of corroded hot-rolled AA8015 sample at Ra≈0.19 µm. (a) image before corrosion at 362-x magnification; (b-d) images after corrosion at increased magnifications. 122

Figure 4-65: SEM images of corroded hot-rolled AA8015 sample at Ra≈0.10 µm. (a) image before corrosion at 254-x magnification; (b-d) images after corrosion at increased magnifications. 122
Figure 4-81: 3-D FE Model pictures showing equivalent Von Mises stress distribution (vertical scale bar) in the roll bite during the cold rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4.................................................................................................................. 132

Figure 4-82: Equivalent Von Mises stress vs plastic strain for the four pass schedules at the roll-strip interface in 2-D FE models.............................................................................................................. 133

Figure 4-83: Equivalent Von Mises stress vs plastic strain for the four pass schedules at the roll-strip interface in 3-D FE models ............................................................................................. 133

Figure 4-84: 2-D FE Model pictures showing normal stress distribution (vertical scale bar) in the roll bite during cold-rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4 ................................................................................................................................................ 134

Figure 4-85: 2-D FE Model pictures showing shear stress distribution (vertical scale bar) in the roll bite during cold-rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4 .. 135

Figure 4-86: 3-D FE Model pictures showing normal stress distribution (vertical scale bar) in the roll bite during cold-rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4 ................................................................................................................................................ 135

Figure 4-87: 3-D FE Model pictures showing shear stress distribution (vertical scale bar) in the roll bite during cold-rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4 .. 136

Figure 4-88: Nodal normal and shear stress variation-time histories for the four pass schedules at the roll-strip interface for 2-D FE models .................................................................................... 136

Figure 4-89: Nodal normal and shear stress variation-time histories for the four pass schedules at the roll-strip interface for 3-D FE models .................................................................................... 137

Figure 4-90: 2-D FE Model time histories for each pass schedule showing (a) roll separating force and (b) roll torque values ........................................................................................................ 138

Figure 4-91: 3-D FE Model time histories for each pass schedule showing (a) roll separating force and (b) roll torque values ........................................................................................................ 139

Figure 4-92: Comparison of predicted roll-separating force and industrial data at varying pass schedules................................................................................................................................. 140

Figure 4-93: Pictures showing contact friction force distribution (vertical scale bar) in the roll bite for deformable-rigid contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work)................................................................. 141

Figure 4-94: Pictures showing contact friction force distribution (vertical scale bar) in the roll bite for deformable-deformable contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work)................................................................. 141

Figure 4-95: Nodal contact frictional force variation-time histories for the four pass schedules at the roll-strip interface deformable-rigid contact algorithm ................................................................. 142

Figure 4-96: Nodal contact frictional force variation-time histories for the four pass schedules at the roll-strip interface deformable-deformable contact algorithm ................................................................. 142

xxiii
Figure 4-97: Pictures showing plastic strain rate distribution (vertical scale bar) in the roll bite for deformable-rigid contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work) ................................................ 143

Figure 4-98: Pictures showing plastic strain rate distribution (vertical scale bar) in the roll bite for deformable-deformable contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work) ..................................... 143

Figure 4-99: Nodal plastic strain rate variation-time histories for the four pass schedules at the roll-strip interface deformable-rigid contact algorithm ................................................................. 144

Figure 4-100: Nodal plastic strain rate variation-time histories for the four pass schedules at the roll-strip interface deformable-deformable contact algorithm ....................................................... 144

Figure 4-101: Pictures showing Von Mises stress distribution (vertical scale bar) in the roll bite for deformable-rigid contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work) ................................................ 145

Figure 4-102: Pictures showing Von Mises stress distribution (vertical scale bar) in the roll bite for deformable-deformable contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work) ..................................... 145

Figure 4-103: Pictures showing normal stress distribution (vertical scale bar) in the roll bite for deformable-rigid contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work) ................................................ 146

Figure 4-104: Pictures showing shear stress distribution (vertical scale bar) in the roll bite for deformable-rigid contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work) ................................................ 147

Figure 4-105: Pictures showing normal stress distribution (vertical scale bar) in the roll bite for deformable-deformable contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work) ................................................ 147

Figure 4-106: Pictures showing shear stress distribution (vertical scale bar) in the roll bite for deformable-deformable contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work) ................................................ 148

Figure 4-107: Nodal normal and shear stress variation-time histories for the four pass schedules at the roll-strip interface deformable-rigid contact algorithm ................................................................. 148

Figure 4-108: Nodal normal and shear stress variation-time histories for the four pass schedules at the roll-strip interface deformable-deformable contact algorithm ................................................................. 149

Figure 4-109: Pictures showing heat flux distribution (vertical scale bar) in the roll bite for deformable-rigid contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work) ................................................ 150
Figure 4-110: Pictures showing heat flux distribution (vertical scale bar) in the roll bite for deformable-deformable contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work) .......................................................... 150

Figure 4-111: Nodal heat flux variation-time histories for each pass schedule at the roll-strip interface (a) deformable-rigid contact algorithm; and (b) deformable-deformable contact algorithm ........................................................................................................................................... 151

Figure 4-112: Pictures showing temperature distribution (vertical scale bar) in the roll bite for deformable-rigid contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work) .......................................................... 152

Figure 4-113: Pictures showing temperature distribution (vertical scale bar) in the roll bite for deformable-deformable contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work) .......................................................... 152

Figure 4-114: Nodal temperature variation-time histories for each pass at roll-strip interface (a) deformable-rigid contact algorithm; and (b) deformable-deformable contact algorithm ....... 153

Figure 4-115: Coupled thermo-mechanical 2-D FE Model time histories for each pass schedule in deformable-rigid contact algorithm showing (a) roll separating force and (b) roll torque values ........................................................................................................................................... 154

Figure 4-116: Coupled thermo-mechanical 2-D FE Model time histories for each pass schedule in deformable-deformable contact algorithm showing (a) roll separating force and (b) roll torque values ........................................................................................................................................... 155

Figure 4-117: Predicted roll-separating force compared with industrial data at varying pass schedule/ percentage of the cold work ............................................................................................................. 156
LIST OF TABLES

Table 2-1: Principal alloying elements in the wrought alloy designation system [73] .................. 12
Table 2-2: Classification of wrought aluminium alloys based on thermal treatment [74] ............... 15
Table 3-1: Detailed description of Achenbach 4Hi reversing cold-rolling mill at TARM ................. 49
Table 3-2: Chemical compositions of the AA8015 specimen (weight %) ................................. 51
Table 3-3: Material data and mesh density .................................................................................. 62
Table 3-4: AA8015-alloy variable hardening model ................................................................... 64
Table 3-5: Material data and mesh density .................................................................................. 70
Table 3-6: Thermal and mechanical properties of AA8015-alloy metal and work roll ................. 70
Table 4-1: Summary of stress-strain graph results for the hot-rolled AA8015 specimen 7 mm thickness for three samples ......................................................................................... 75
Table 4-2: Summary of stress-strain graph results for reversing cold-rolled AA8015 specimen 1.2 mm thickness for three samples .............................................................................. 77
Table 4-3: Summary of stress-strain graph results for non-reversing cold-rolled AA8015 specimen 1mm thickness for three samples .................................................................................. 78
Table 4-4: Summary of stress-strain graph results for non-reversing cold-rolled AA8015 specimen 2 mm thickness for the three samples .......................................................................... 80
Table 4-5: Summary of stress-strain graph results for non-reversing cold-rolled AA8015 specimen 3mm thickness for the three samples .............................................................................. 82
Table 4-6: Summary of stress-strain graph results for non-reversing cold-rolled AA8015 specimen 4 mm thickness for the three samples .......................................................................... 84
Table 4-7: Summary of stress- strain graph results for non-reversing cold-rolled AA8015 specimen 5 mm thickness for the three samples .............................................................................. 86
Table 4-8: Summary of stress-strain graph results for non-reversing cold-rolled AA8015 specimen 6 mm thickness for the three samples .............................................................................. 88
Table 4-9: Micro-hardness measurements for rolled specimen samples ........................................... 90
Table 4-10: Major ion composition of sea water at 3.5% salinity [195] ......................................... 103
Table 4-11: Surface roughness (Ra) values of corrosion samples under various surface conditions .................................................................................................................................................. 103
Table 4-12: Open circuit potential (Eoc) for hot-rolled AA8015 samples against Ag/AgCl with varying degrees of surface roughness .............................................................................. 108
Table 4-13: Open circuit potential (Eoc) for cold-rolled AA8015 samples against Ag/AgCl with varying degrees of surface roughness .............................................................................. 108
Table 4-14: Corrosion rate analysis of hot-rolled AA8015-alloy at Ra≈1.37 µm ............................ 112
Table 4-15: Corrosion rate analysis of hot-rolled AA8015-alloy at Ra≈0.65 µm ............................ 112
Table 4-16: Corrosion rate analysis of hot-rolled AA8015-alloy at Ra≈0.19 µm......................... 113
Table 4-17: Corrosion rate analysis of hot-rolled AA8015-alloy at Ra≈0.10 µm......................... 113
Table 4-18: Corrosion rate analysis of cold-rolled AA8015-alloy at Ra≈1.54 µm ....................... 113
Table 4-19: Corrosion rate analysis of cold-rolled AA8015-alloy at Ra≈0.83 µm....................... 114
Table 4-20: Corrosion rate analysis of cold-rolled AA8015-alloy at Ra≈0.18 µm....................... 114
Table 4-21: Corrosion rate analysis of cold-rolled AA8015-alloy at Ra≈0.04 µm ....................... 114
Table 4-22: Summary of the mean values of polarization resistance and corrosion rates of hot-rolled
AA8015-alloy at different surface roughness values.............................................................. 116
Table 4-23: Summary of the mean values of polarization resistance and corrosion rate of cold-rolled
AA8015-alloy at different surface roughness values.............................................................. 116
Table 4-24: Weight analysis of hot- and cold-rolled AA8015-alloy before and after electrochemical
corrosion testing...................................................................................................................... 116
Table 4-25: Predicted roll separating force and roll torque magnitudes for coupled thermo-
mechanical 2-D FE model simulation..................................................................................... 155
LIST OF PUBLICATIONS

1. Olaogun, O., Akinlabi, E.T. and Oluwole, O.O. ‘Study of the properties of hot- and cold-rolled Al 8015 alloy processed by sustainable reversible rolling mill’, World Review of Science, Technology and Sustainable Development (accepted for publication-2018)


4. Olaogun, O., Edberg, J., Lindgren, L-E., Oluwole, O.O., Akinlabi, E.T., Modelling and Simulation of the first pass in Industrial Cold Rolling Process of Aluminium 8015 Alloy. (Abstract and full manuscript accepted at the 11th South African Conference on Computational and applied Mechanics)

5. Olaogun, O., Akinlabi, E.T., Corrosion behaviour of hot-rolled aluminium 8015-alloy at varying surface roughness values. (Abstract submitted to Elsevier conference on wear and full manuscript under development)
GLOSSARY OF TERMS

A

Ag/AgCl – Silver/silver chloride reference electrode. Potential dependent on concentration of chloride ions within the electrode system.

Alloy – a substance having metallic properties and being composed of two or more chemicals.

Alloying element – the alloying element is an element added to and remaining in the metal, which changes its structure and properties.

Aluminium foil – aluminium metal in sheet form less than 0.15 mm thick

Ambient temperature – the temperature that exists at nodes on a finite element model where nodal and/or elemental temperatures are not defined. For non-linear static analysis, ambient temperature can vary with time.

Anisotropy – anisotropy means that physical properties of a crystalline substance are different, depending on its crystal orientations.

Annealing – annealing is a thermal treatment to heat metallic materials and others at an appropriate temperature and then cool slowly to obtain uniform structures, or for removing the internal stress of the materials.

Anode – the electrode of an electrochemical cell at which oxidation occurs, in which a positive potential (voltage) is applied against the facing cathode (electron source). It is usually the electrode where corrosion occurs and metal ions enter the solution.

Anodic reaction – the electrochemical (oxidation) reaction in which electrons are freed into the electric circuit and the oxide species are formed.

B

Boundary condition – enforced environmental conditions on a finite element model. Boundary conditions include restraints, constraints, temperatures, and mechanical loads.

Bulk forming – a forming process, such as extrusion, forging, rolling, and drawing, in which the input material is in billet, rod, or slab form and a considerable increase in surface-to-volume ratio in the formed part occurs under the action of largely compressive loading.

C

Cathode – an electrode, to which a negative potential (voltage) is applied against the facing anode. Cathode in electrochemical corrosion means the part of an electrolytic cell at which a cathodic (reduction) reaction occurs.
**Cathodic reaction** – the electrochemical (reduction) reaction by which electrons are consumed. This reaction is typically either the hydrogen evolution reaction or the oxygen reduction reaction.

**Cluster mill** – a rolling mill in which each of the two working rolls of small diameter is supported by two or more larger-diameter back-up rolls.

**Coefficient of friction** – this is a dimensionless ratio of the friction force (F) between two bodies to the normal force (N) pressing these bodies together.

**Cold mill** – this is a mill for cold rolling of sheet or strip.

**Cold work** – this is a permanent strain in a metal accompanied by strain hardening.

**Cold working** – this is the process of deforming metal plastically under conditions of temperature and strain rate that induce strain hardening. Usually but not necessarily conducted at room temperature.

**Cold-rolled sheets** – a metal mill product produced from a hot-rolled pickled coil that has been given substantial cold reduction at room temperature. The resulting product usually requires further processing to make it suitable for most common applications. The usual end product is characterised by improved surface, greater uniformity in thickness and improved mechanical properties compared to hot-rolled sheet.

**Continuous mill** – a rolling mill consisting of a number of strands of synchronized rolls (in tandem) in which metal undergoes successive reductions as it passes through the various strands.

**Coolant** – the liquid used to cool the work during grinding and to prevent it from rusting. It also lubricates, washes away chips and grits, and aids in obtaining a finer finish.

**Corrosion** – the spontaneous process whereby an anodic reaction and a corresponding cathodic reaction take place on the same metallic component in an electrolyte leading to production of metal ionic species. For corrosion to proceed, both the anodic reaction and the cathodic reaction must be thermos-dynamically capable of proceeding and must balance.

**Corrosion current (density)** – the current flowing in a corrosion ‘local cell’. The anodic and cathodic current must be equal, but the current densities may be different depending on the area ratio. The corrosion current is closely related to the concept of corrosion potential.

**Corrosion rate** – this is the amount of corrosion occurring in unit time.

**Corrosion resistance** – this is the ability of a material to withstand contact with ambient natural factors or those of a particular artificially created atmosphere without degradation or change in properties.
Corrosion resistance – this is the ability of a metal to withstand corrosion in a given corrosion system.

Counter electrode – an electrode in a three-electrode cell that is used only to make an electrical connection to the electrolyte so that a current can be applied to the working electrode.

Current – a measure of the rate of flow of electricity in a conductor and usually expressed in amperes (A) or milliamps (mA).

Current density – current passing across unit area of surface, usually expressed as milliamps per square metre mA/m²) or amps per square metre (A/m²)

D

Deformation – this is a change in the form of a body, due to stress, heat, change in microstructure, chemical condition or other causes.

Discretization – the process of dividing geometry into smaller pieces (finite elements) to prepare for analysis, known as meshing.

Dispersoid – finely divided particles of relatively insoluble constituents visible in the microstructure of certain metallic alloys.

Displacement – the distance, translational and rotational, that a node travels from its initial position to its post-analysis position. The total displacement is represented by components in each of the three translational directions and the three rotational directions.

Ductility – the ability of a material to deform plastically before fracture.

Dwell time – the period of time after the rotating tool has been plunged into the work, and for which it remains stationary, generating frictional heat and plasticizing the materials, before commencing the traverse along the joint. It is measured in seconds.

Dynamic modelling – a modelling process where consideration as to time effects in addition to spatial effects are included. A dynamic model can be the same as a static model or it can differ significantly depending upon the nature of the problem.

E

Elastic deformation – this is the deformation of the material that is recovered when force is applied to it.

Elastic limit – this is the greatest stress, which a material is capable of sustaining without any sign of permanent strain remaining upon complete release of the stress.

Elastic region – a material is said to be stressed within the elastic region, when the working stress does not exceed the elastic limit.
**Electrochemical cell** – this is electrochemical device which directly converts chemical energy into electrical energy or vice versa when a chemical reaction is occurring in the cell. It usually consists of two or three metal electrodes immersed into an aqueous solution (electrolyte) with electrode reactions occurring at the electrode-solution surfaces.

**Electrochemical corrosion** – this is refers to as corrosion which occurs when current flows between cathodic and anodic areas on metallic surfaces.

**Electrochemical reaction** – this is an oxidation/reduction reaction that occurs in an electrochemical cell. The essential feature is that the simultaneously occurring oxidation-reduction reaction are spatially separated.

**Electrode** – in this context it refers to either the positive or negative conductor in an electrochemical cell.

**Electrode potential** – it is the electrical potential difference between an electrode, usually working electrode, and a reference electrode.

**Electrode potential** – the potential of an electrode within an electrolyte measured with respect to a reference electrode. Measurement indicates whether the electrochemical reactions taking place at the electrode surface are predominantly anodic or cathodic and thus can give an indication of the condition of the electrode material.

**Electrolyte** – a chemical compound (salt, acid, or base) that dissociates into electrically charged ions when dissolved in a solvent. The resulting electrolyte solution is an ionic conductor of electricity.

**Electrolyte** – a solution which conducts electric current by the transport of ionic species through which the corrosion and cathodic protection currents flow.

**Element** – in the finite element method the geometry is divided up into elements, much like basic building blocks. Each element has nodes associated with it. The behaviour of the element is defined in terms of the freedoms at the nodes.

**Element assembly** – individual element matrices have to be assembled into the complete stiffness matrix. This is basically a process of summing the element matrices. This summation has to be of the correct form. For the stiffness method the summation is based upon the fact that element displacements at common nodes must be the same.

**Elongation** – the increase in gauge length of a body subjected to a tension force, referenced to gauge length of a body. This is usually expressed as a percentage of the original gauge length.

**Elongation (%)** – the total per cent increase in the gauge length of a specimen after a tensile test.
Emissivity – this is the ratio of the amount of energy or of energetic particles radiated from a unit area of a surface to the amount radiated from a unit area of an ideal emitter under the same conditions.

Energy dispersive X-ray spectroscopy – is an element analysis method. Characteristic X-rays generated from a specimen are detected by a semiconductor detector and converted into electric signals.

Engineering strain – this is a dimensionless value that is the change in length ($\Delta L$) per unit length of the original linear dimension ($L_0$) along the loading axis of the specimen; that is $e = \frac{\Delta L}{L_0}$ is the amount that a material deforms per unit length in a tensile test.

Equiaxed grain structure – a structure in which the grains have approximately the same dimensions in all directions.

Equilibrium – a state of dynamic balance between the opposing actions, reactions, or velocities of a reversible process.

Equivalent material properties – equivalent material properties are defined where real material properties are smeared over the volume of the element. Typically, for composite materials the discrete fibre and matrix material properties are smeared to give average equivalent material properties.

Equivalent stress – a three-dimensional solid has six stress components. If material properties have been found experimentally by a uniaxial stress test, then the real stress system is related to this by combining the six stress components to a single equivalent stress. There are various forms of equivalent stress for different situations. Common ones are Tresca, Von-Mises, Mohr-Coulomb and Drucker-Prager.

Etchant – a chemical solution used to etch a metal to reveal the structural details.

Etching – subjecting the surface of a metal to preferential chemical or electrolytic attack to reveal the structural details for metallography subsequent examination.

Exact solutions – solutions that satisfy the differential equations and the associated boundary conditions exactly. There are very few such solutions and they are for relatively simple geometries and loadings.

Finite element analysis – is one of numerical analytical methods to obtain an approximate solution of partial differential equations that are difficult to solve analytically.

Finite element modelling (FEM) – the process of setting up a model for analysis, typically involving graphical generation of the model geometry, meshing it into finite elements, defining material properties, and applying loads and boundary conditions.
**Fixed-boundary conditions** – all degrees of freedom are restrained for this condition. The nodes on the fixed boundary cannot move: translation or rotation.

**Flat-rolled aluminium** – this refers to aluminium metal processed on rolls with flat faces as opposed to grooved or cut faces. Flat-rolled products include plate, sheet and strip.

**Flow stress** – this is the stress required to produce plastic deformation in a solid metal.

**Four-high mill** – a type of rolling mill, commonly used for flat-rolled mill products, in which two large-diameter back-up rolls are employed to reinforce two smaller work rolls, which are in contact with the product. Either the work rolls or the back-up rolls may be driven.

**Friction** – this is the reaction force resulting from surface interaction and adhesion during sliding. The friction coefficient is defined as the friction force divided by the load.

**G**

**Galvanic corrosion** – corrosion associated with the current of a galvanic cell consisting of two dissimilar conductors in an electrolyte or two similar conductors in dissimilar electrolytes.

**Gauge length** – this is the original length of that portion of the specimen over which strain, change of length and other characteristics are measured.

**Gauge thickness** – this is the thickness of sheet or plate

**Grain** – an individual crystal in a polycrystalline material.

**Grain boundary** – an interface separating two grains, whereby the orientation change is very small; the boundary is sometimes referred to as a sub-boundary structure.

**Grain growth** – this is a phenomenon, which occurs when the temperature of a metal is raised; the grains begin to grow and their size may eventually exceed the original grain size.

**Grain size** – a measure of the areas or volumes of grains in a polycrystalline metal or alloy, usually expressed as an average, when the individual sizes are fairly uniform. Grain size is reported in terms of the number of grains per unit area or volume, the average diameter, or as a number derived from the area measurements.

**Grinding** – removing material from the surface of a work piece by using a grinding wheel or abrasive grinding papers.

**H**

**Hardening** – This is the increasing hardness of metals by suitable treatment, usually involving heating and cooling.
Hardness – this is a term used for describing the resistance of a material to plastic deformation. It is also refer to as a measure of the resistance of a material to surface indentation or abrasion.

Hardness test – this measures the resistance of a material to penetration by a sharp object.

Heat-treatable alloy – an alloy that can be hardened by heat treatment.

Heat treatment – heating and cooling a solid metal or alloy in such a way as to obtain desired conditions or properties.

Homogeneous – the chemical composition and the physical state of any physically small portion, and one, which is same as that of any other portion.

Hot working – a deformation under conditions that result in recrystallization.

Interface – an interface is a boundary surface between two different phases.

Isotropic – having uniform properties in all directions. The measured properties of an isotropic material are independent of the axis of testing.

Macrograph – a graphic reproduction of a prepared surface of a specimen at a magnification not exceeding 25x.

Materials characterization – the use of various analytical methods (spectroscopy, microscopy etc.) to describe those features of composition and structure of a material that are significant for a particular preparation, study of properties, or use.

Maximum stress – the stress having the highest algebraic value in the stress cycle, tensile stress being considered positive and compressive stress negative.

Mechanical polishing – is a physical polishing technique used for specimen preparation of Optical microscopy, SEM and TEM. The common techniques includes: manual polishing using water-resistant paper, rotational polishing device-based polishing using diamond particles and dimple grinder-based polishing using corundum particles.

Mechanical properties – the properties of a material that reveal its elastic and inelastic behaviour when force is applied, thereby indicating its suitability for mechanical applications; for example, modulus of elasticity, tensile strength, elongation, and hardness.

Mechanical properties – these are the properties of a material that reveal its elastic or inelastic behaviour, when a force is applied, indicating the suitable mechanical applications.

Mechanical testing – the methods by which the mechanical properties of a metal are determined.
**Melting point** – the temperature at which a pure metal changes from solid to liquid; the temperature at which the liquid and the solid are at equilibrium.

**Metal** – a substance in which ions are bound with each other through free electrons. The crystal structure of a metal is a face-centered cubic structure, a body-centered cubic structure, or a hexagonal close-packed structure. A metal exhibits high electric conductivity, high thermal conductivity and high light reflectivity, and is highly malleable as well as highly ductile.

**Metal** – an opaque lustrous elemental chemical substance that is a good conductor of heat and electricity and, when polished, a good reflector of light. Most elemental metals are malleable and ductile and are denser than the other elemental substances.

**Metallography** – the study of the structure of metals and alloys by various methods, especially by optical and electron microscopy.

**Micrograph** – a graphic reproduction of the surface of a specimen at a magnification greater than 25x.

**Microhardness** – the hardness of a material as determined by forcing an indenter such as a Vickers or Knoop indenter into the surface of a material under very light load; usually the indentations are so small that they must be measured with a microscope.

**Microhardness test** – a micro indentation hardness test using a calibrated machine to force a diamond indenter of specific geometry, under a test load of 1 to 1000 gram-force into the surface of the test material and to measure the diagonal or diagonals optically.

**Microstructure** – the structure of a prepared surface of a metal, as revealed by a microscope at a particular magnification.

**Mill** – a factory in which metals are hot worked, cold worked, or melted and cast into standard shapes suitable for secondary fabrication into commercial products.

**Model** – the model is the empirical mathematical model that is fitted to the data.

**Modulus of elasticity (E)** – the measure of rigidity or stiffness of a material; the ratio of stress, below the proportional limit to the corresponding strain.

**Multimeter** – an instrument that can be used for the measurement of more than one parameter. Typically, it can be used to measure current, potential, and resistance.

**Normal stress** – the stress component that is perpendicular to the plane on which the forces act. Normal stress may be either tensile or compressive.
Offset yield strength – the stress at which the strain exceeds by a specific amount (the offset) an extension of the initial, approximately linear, proportional portion of the stress-strain curve. It is expressed in force per unit area.

Over potential – this is the difference in the electrode potential of an electrode between its equilibrium potential and its operating potential when a current is flowing. The over potential represents the extra energy needed to force the electrode reaction to proceed at a required rate.

Oxidation – a reaction in which there is an increase in valence resulting from a loss of electrons.

Parameter – the minimum and maximum parameters that would describe the operating range of a variable.

Pass – a single transfer of metal through a stand of rolls.

Passive – a metal characterized by low corrosion rate in a certain potential range whose oxidation is the predominant reaction.

Passivity – this is the reduction in the anodic rate of reaction because of the formation of a protective film of oxide.

pH – the negative logarithmic value of the hydrogen ion concentration used to express the acidity or alkalinity of a solution. Values below 7 are progressively more acidic, 7 is neutral and values above 7 are progressively more alkaline.

Pitting – corrosion of a metal surface, confined to a point or small area that takes the form of cavities.

Pits – it is the result of localized corrosion confined to a small area in the metal surface, in the form of a small cavity.

Plane strain – the stress condition in linear elastic fracture mechanics in which there is zero strain in a direction normal to both the axis of applied tensile stress and the direction of crack growth.

Plane stress – the stress condition in linear elastic fracture mechanics in which the stress in the thickness direction is zero.

Plastic deformation – the permanent distortion of materials under applied stresses that strain the material beyond its elastic limit.
Plastic deformation – this is the distortion of material continuously and permanently in any direction. The deformation that remains or would remain permanent after the release of the stress that caused it.

Plate - a flat rolled metal product of some minimum thickness and width arbitrarily dependent on the type of metal. Plate thicknesses commonly range from 6 to 300 mm.

Poisson’s ratio – the absolute value of the ratio of transverse (lateral) strain to the corresponding axial strain resulting from uniformly distributed axial stress below the proportional limit of the material.

Polarization – an application of current causes the potential of an electrode to increase from its static or theoretical decomposition potential as the current is increased. This potential change, termed polarisation, is the result of several changes which occur due to the passage of the current.

Polarization curve – a plot of current density versus electrode potential for a specific electrode–electrolyte combination.

Polished surface – this is a surface that reflects a large proportion of the incident light in a peculiar manner.

Polishing – smoothing metal surfaces, often to a high luster, by rubbing the surface with a fine abrasive, usually contained in a cloth or other soft lap.

Potential – the driving influence of an electrochemical reaction.

Potentiostat – this is a device used in electrochemical corrosion testing. It is an electronic instrument that controls the electrical potential between the working and reference electrodes of a three-electrode cell at a pre-set value. It forces whatever current is necessary to flow between the working and counter electrodes to keep the desired potential, as long as the needed cell voltage and current do not exceed the compliance limits of the potentiostat.

Predicted value – this is the value of the response predicted by the mathematical model.

Recrystallization – this is a change from one crystal structure to another, such as that occurring upon heating and/or cooling through a critical temperature.

Recrystallization temperature – the approximate minimum temperature at which complete recrystallization of a cold-worked metal occurs within a specified time.

Reference electrode – the standard test cell against which potential movement on a surface is measured. In electrochemical corrosion testing, a silver/silver chloride electrode is usually utilized.
**Residual stress** – this is the stress in a body, which is at rest, in equilibrium, and at a uniform temperature in the absence of any external force.

**Roll-bite angle** – It is the angle that is formed between two lines crossing at the roll centre; where the first line passes through the entry point; and the second line passes through the exit point of the deformation zone.

**Roll contact length** – This is a horizontal projection of the arc of contact of the roll to the workpiece during the rolling process.

**Roll forming** – metal forming through the use of power-driven rolls whose contour determines the shape of the product.

**Rolling** – the reduction of the cross-sectional area of metal stock, or the general shaping of metal products through the use of rotating rolls.

**Rolling direction** – this refers to the direction in which the billet was rolled during the sheet metal plate manufacture.

**Rolling mills** – machines used to decrease the cross-sectional area of metal stock and to produce certain desired shapes as the metal passes between rotating rolls mounted in a framework comprising a basic unit called a stand.

**Roughness** – the microscopic peak-to-valley distances of surface protuberances and depressions.

**Rust** – a visible corrosion product consisting of hydrated oxides of iron.

**Sample** – a portion of a material intended to be representative of the whole.

**Scanning electron microscope** – an electron microscope, in which the image is formed by a beam operating simultaneously with an electron probe scanning the object.

**Shear** – the type of force that causes or tends to cause two contiguous parts of the same body to slide relative to each other in a direction parallel to their plane of contact.

**Shear stress** – the stress component tangential to the plane on which the forces act.

**Sheet** – a flat-rolled metal product of some maximum thickness and minimum width arbitrarily dependent on the type of metal.

**Single-stand mill** – a rolling mill designed such that the product contacts only two rolls at a given moment.

**Solid solution** – when two or more kinds of substances are mixed and have a uniform structure, the mixed crystal is called a solid solution.

**Solution potential** – an electrode potential where half-cell reaction involves only the metal electrode and its ion.
Specimen – a test object, often of standard dimensions and/or configuration that is used for destructive or non-destructive testing.

Stand – a piece of rolling mill equipment containing one set of work rolls.

Strain – the unit of change in the size or shape of a body due to force.

Strain hardening – an increase in the hardness and strength of metals caused by plastic deformation at temperatures below the recrystallization range. It is also known as work hardening.

Strain rate – the time rate of straining for the usual tensile test. Strain as measured directly on the specimen gauge length is used for determining strain rate.

Stress – this is the load applied to a piece of material; and it tends to cause deformation, which is resisted by the internal forces set up within the materials, which are referred to as stresses. The intensity of the stress is estimated as the force acting on the unit area of the cross-section. It is expressed mathematically as Newton per square meter or Pascal.

Strip – a flat-rolled metal product of some maximum thickness and width arbitrarily dependent on the type of metal; narrower than sheet.

Surface finish – the geometric irregularities in the surface of a solid material. It is a condition of a surface as a result of final treatment.

Surface roughness – fine irregularities in the surface texture of a material, usually including those resulting from the inherent action of the production process. Surface roughness is usually reported as the arithmetic roughness average, \( R_a \), and is given in micro-metres or in micro-inches.

Tafel slope – this is the slope of the straight line portion of a polarization curve, usually occurring at more than 50 mV from the open-circuit potential, when presented in a semi-logarithmic plot in terms of volts per logarithmic cycle of current density.

Tandem mill – a rolling mill consisting of two or more stands arranged so that the metal being processed travels in a straight line from stand to stand. In continuous rolling, the various stands are synchronized so that the strip can be rolled in all stands simultaneously.

Tensile strength – this is the maximum tensile stress, which a material is capable of sustaining. The tensile strength is calculated from the maximum load during a tension test carried out to rupture and from original cross-sectional area of the specimen.

Tensile test – this measures the response of a material to a slowly applied axial force. The yield strength, tensile strength, modulus of elasticity and ductility are thereby obtained.
Thermal analysis – a method for determining transformations in a metal by noting the temperatures at which thermal arrests occur. These arrests are manifested by changes in slope of the plotted or mechanically traced heating and cooling curves.

Thermal stresses – stresses in a material resulting from non-uniform temperature distribution.

Thermo-mechanical working – a general term covering a variety of metal forming processes combining controlled thermal and deformation treatments to obtain synergistic effects, such as improvement in strength without loss of toughness.

Toughness – ability of a material to absorb energy and deform plastically before fracturing.

Two-high mill – a type of rolling mill in which only two rolls, the working rolls, are contained in a single housing.

V

Vickers hardness number (HV) – this is a number related to the applied load and the surface area of the permanent impression made by a square-based pyramid diamond indenter.

Vickers hardness test – a micro-indentation hardness test employing a 1360 diamond pyramid indenter (Vickers) and variable loads, enabling the use of one hardness scale for all ranges of hardness.

W

Warm working – a thermo-mechanical treatment that involves the deformation of metals at elevated temperatures below the recrystallization temperature.

Work piece – the component to be welded.

Working electrode – this is the test or specimen electrode in an electrochemical cell. It is an electronically conducting part of an electrochemical cell. It can be a simple metallic structure such as rods and sheets.

Y

Yield strength – this is the stress at which a material exhibits a specified deviation from proportionality of stress and strain. An offset of 0.2% is used for many metals.

Yield stress – this is the stress level in a material at or above the yield strength but below the ultimate strength, that is, a stress in the plastic range.

Young’s modulus – a term used synonymously with modulus of elasticity. The ration of tensile or compressive stresses to the resulting strain.
CHAPTER 1

INTRODUCTION

1.1 Background

The useful lifespan of any component or device is always established at its design and manufacturing stage [1]. In extractive metallurgy, large billets have to be reduced by mechanical deformation processes such as forging, rolling and extrusion for further reduction and change in their shapes. There are three basic temperature ranges in metal forming at which the metal (workpiece) can be formed which are hot working, warm working and cold working [2]. Cold working is a strengthening mechanism that involves plastic deformation. This strengthening mechanism is mostly utilized in non-brittle metals. In addition, cold working takes place when the processing temperature of the mechanical deformation of the ductile metal is below the recrystallization temperature [3-5]. Cold working in mechanical rolling process is eminent as compared to pressing, drawing, spinning and extruding.

The cold working in rolling process, known as cold rolling, involves deforming of the ductile metal by use of rolls at low temperatures, especially at temperatures below the recrystallization temperature of the metal. Cold rolling processes are achieved by use of rolling mills to produce metal sheets of a certain thickness. The vast majority of cold rolled metal is in the form of flat rolling, although, there exist cold pilgering of seamless tube. Worth noting is the fact that cold rolling has enormous benefits in its ability to manufacture products from relatively large pieces of metal at very high speed in a continuous manner with good surface finish, highly accurate tolerances and stronger products. Addition to these benefits are elimination of shrinkage effect, increased hardness as well as the elastic limit, and decrease in ductility due to strain hardening effect [2, 4, 6, 7].

Research on rolled metals was earlier carried out in the middle of the 20th century. The first recorded study by Mizuno et al. [8] proposed innovative parameter in solving the friction and lubrication in the cold rolling of thin sheet metals. Subsequent investigation by Tsukatani et al. [9] examined high-strength hot-rolled sheet steel developed by transformation-induced plasticity of retained austenite in 0.2% carbon sheet steels. Experimental analysis revealed great influence of the silicon and manganese inclusion on the microstructure and mechanical properties of the hot-rolled sheet steels. Likewise, several material characterizations in cold-rolled steel sheets by various scholars [10-18] also confirmed the effect of cold rolling on the mechanical properties of the metal. Equally, experimental examination on rolled aluminium alloy series have been reported [19-39], however, there is no study considering the effect of reversing and non-reversing cold rolling process on aluminium 8015-alloy.
Therefore, this research work will focus on an extensive in-depth experimental investigation and system modelling and simulation for the cold rolling process of industrial rolled aluminium 8015-alloy using advanced computer modelling technique. Computerised modelling techniques will be more efficient to analyse complex loading including the static and dynamic forces plus temperature variations, especially during the cold rolling processes.

1.2 Motivation

Research in cold rolling of metals especially 8-series aluminium family are limited and a grey area of study. Moreover, preliminary study on slip line field analysis in cold rolling mill revealed that further detailed and advanced characterization is required on cold rolled product, especially on the evolving properties of the cold rolled metal [40, 41]. In addition, the modelling and simulation of the cold rolling process is of importance. To achieve a more accurate approach, there is need to develop models that can simulate the cold rolling process and the observed heat transfer using advanced computer numerical software. This will investigate and proffers preventive measures coupled with validating using industrial measurement results. Previous studies [42-53] revealed that material models utilized in finite element simulation of metal forming processes are often a variety of constitutive equations that are either phenomenological or to a varying degree physically based due to the complex material behaviour. However, this research uniqueness focus on experimental technique to determine the material model of the aluminium 8015-alloy validated by inverse modelling method based on finite element model to derive the plastic flow properties from tensile specimens of aluminium 8015 alloy.

1.3 Problem statement

The trend in the use of aluminium alloys for the automotive, construction and packaging industries is still high, despite the successes recorded in the use of composites materials.

The open literature [19-39] have reported large amount of studies carried out using aluminium and its alloys, however, sufficient studies have not been reported in the open literature on aluminium series-8 family, especially on aluminium 8015-alloy, yet this aluminium alloys has enormous applications. Its applications are not only limited to household or domestic use but also for the heat-sink device, air-condition foil, radiators as well as Aluminium doors and windows. Similarly, researchers have not comprehensively explored into the cold rolling process, with emphasis on the thermal analysis of the cold rolling process. This has been due to the widespread assumption of its insignificant impact during the cold rolling process whereas it is important to have knowledge on the inherent properties resulting from the cold rolling process.
In addition, the material model utilized in finite element simulation of metal forming processes reported [42-53] are often a variety of constitutive equations that are either phenomenological or to a varying degree physically based due to the complex material behaviour.

In the current study, rolled aluminium 8015-alloy was analysed through the metallographic testing, mechanical testing, and electrochemical corrosion test analysis, which has successfully investigated into the material behaviour. Furthermore, two-dimensional and three-dimensional finite element models for the cold rolling process were developed to simulate the rolling process and the thermo-mechanical behaviours during the process. The finite element model simulated results were validated with the computerized industrial measurement.

1.4 Significance of the research

Recent activities in the aluminium industries worldwide show remarkable growth rates. The growth rate is not only eminent in Asia, Europe, and America but also in Africa. In such an environment, it is quite necessary for aluminium industry owners to meet the high-quality product requirement such as excellent surface finish and dimensional accuracy, mill flexibility, enhance production and reduce the production cost. Therefore, the significance of this study lies in the fact that it is not only relevant to hands-on engineers in the manufacturing sector but also to the aluminium manufacturers in tackling or contributing to solving the challenges faced in the aluminium rolling industries and typical application in mill structure design particularly work roll design.

1.5 Research objectives

The goal of this research work is based on the following objectives:

1. To undertake an industrial visit to rolling mill industry in the acquisition of real-world background experience in metal rolling, procurement of rolled aluminium alloy samples and obtaining industrial measurement.

2. To perform experimental investigations on the evolving properties of the rolled aluminium 8015-alloy

3. To explore the corrosion behaviour of the rolled aluminium 8015-alloy by electrochemical corrosion testing.

4. To develop Finite Element Models (FEM) for each pass schedule for the cold rolling process of aluminium 8015 alloy and the thermo-mechanical behaviours during the process in order to validate the industrial measurement.
1.6 Hypothesis statement

The driving force for more research input into the rolling process development is not only limited to experimental investigation into rolled metal at different pass schedules, especially for aluminium 8015-alloy. Also, Finite Element Analysis (FEA) of the cold rolling process coupled with the heat transfer during the process is necessary for better understanding of the process. These, in turn, envisaged that the mechanical testings and metallographic testings would establish a good understanding of the material behaviour of rolled aluminium 8015-alloy. It is also expected that the electrochemical corrosion testing of the rolled aluminium 8015-alloy will adequately document the material behaviour at varying degree of surface roughness. Furthermore, it is envisioned that FEM simulation approach would analyse the thermo-mechanical behaviours and would be able to validate the industrial measurement.

1.7 Organisation of the thesis

This thesis contains six chapters, which are:

Chapter 1: provides a general introduction and background into metal forming processes narrowed down to cold rolling process. The motivation, problem statement, significance of the research, research objectives, and hypothesis statement are presented.

Chapter 2: covers the history of metals, its usage, aluminium, its alloy, roll forming, and forming mills, cold rolling process, rolling mill structure, and model of the rolling process.

Chapter 3: focus on the research methodology. A recap of the goal and objectives were described. The research approach and problems are well articulated. The research procedure of the experimental studies of aluminium 8015-alloy material processed by rolling mill are presented. The experimental study is categorized into metallography testing, mechanical testing, and electrochemical corrosion testing. The chemical composition of the tested aluminium alloy material, as well as the cold rolling process that was applied to the alloy material, is described. In addition, sample preparation for each test and analysis were described. This includes characterization of the microstructure, discussion of the tensile test and hardness test method used to determine the mechanical properties of the alloy material investigated. Furthermore, procedure needed in finite element modelling and simulation of cold rolling process and heat transfer during mechanical deformation process is presented. Simulation of a real-life industrial cold rolling process of AA8015 aluminium alloy was achieved with MSC Marc Mentat, one of the leading FEM software.

Chapter 4: presents the findings and discussion for the experimental investigation and the finite element simulations of the cold rolling process and the coupled thermo-mechanical analysis. The predicted roll separating force was validated with industrial results from Tower Aluminium rolling mill, Sango-Ota, Nigeria.
Chapter 5: provides general conclusions achieved from this research. Recommendations for future work are also suggested.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The main objective of this chapter is to contextualise this study and to elaborate on the main concepts and theories of existing research. This chapter is substantiated with evidence from books, journal articles, dissertations and other scientific sources. The following themes have been reviewed in this chapter: account of metals and its usage; aluminium and its alloy; corrosion of aluminium alloys; roll forming; roll forming mills; cold rolling process; rolling mill structure; model of the rolling process; review of mechanics and mathematical models of rolling process and cold rolling mill system modelling and simulation.

2.2 Background of metals and its use

The discovery of metals greatly contributed to the development of civilisation. Our ancestors used metals to build early tools and weapons. The use of metals was first recorded during the Mesolithic age, between 10000-4500 BC, when our ancestors made use of stone tools and microliths (small trimmed blades) to make a variety of tools. In 6000 BC, metals which were naturally available, such as gold, copper, and meteorite iron were discovered. These metals were used for making ornaments, tools, and weapons [54].

As the knowledge of our early predecessors increased, they discovered that mixing two metals together produced stronger substances. This discovery brought about the “Bronze Age” between 2300 – 700 BC. Subsequently, around 3000 BC, the discovery of smelting ushered in the “Iron Age” around 1200 BC [54]. The Hittites discovered iron around 1500 BC. Iron was predominently used for tools and war weapons. [55, 56]

Around the 19th century, the curiosity and quest for power for supremacy by man brought about the discovery of 24 metals, of which 12 were discovered in the 18th century [54]. Today, about two-thirds of all known elements are metals [57-59].

From the 17th century to the beginning of the industrial revolution, metal working was done by hand through labour-intensive hammering (forging). Metal products or inventions during this period were scarce and expensive [55].

The industrial revolution of the 18th and 19th century brought about the development of power-driven machinery, which steadily substituted many hand tools used in metal manufacturing. Furthermore, the ancient art of hammering (forging) was replaced with pairs of rotating rolls used to transform the shape and thickness of metals. Consequently, the early forging experience gave birth to rolling process at high temperatures, with the knowledge that steel is easier to work at elevated temperature. The introduction of
flywheels, clutches, reversible steam engines and electrical motors contributed to faster steel forming processes, permitting further reduction of the minimum thickness of the rolled products [60].

However, rolling taking place at room temperature is not a recent innovation. Pre-historic cold rolling was recorded in the 14th century when ductile materials like gold and silver were cold worked. The turning point in the rolling technology took place with the introduction of the rolling mill. The first recognised and famous design of rolling mill was achieved by Leonardo da Vinci in 1480 as shown in Figure 2-1. Leonardo da Vinci was able to make a metal material to pass between two cylindrical rollers. Several advances in rolling technology took place between late 16th and early 17th century when rolls pairs were used to roll metals such as gold, lead, and tin to produce complex shapes. The demand for surface finished products in the late 18th century, brought about more sophisticated inventions in the structure of rolling mill to make rolling at room temperature possible. This invention was widely used in the nineteenth century. By the late 19th and 20th century, varieties of hot and cold rolled products of various metals and alloys became commercially available. Latest design and existence of automated rolling mill structure in the late twentieth century has made sheet metal forming the fastest growing segment of the industry [58, 60].

It is, therefore, evident that the advent of new technologies in sheet metal production has led to the production of sophisticated machines, which have positively affected our standard of living.
2.3 Aluminium and its alloys

Aluminium is the third most abundant element in the earth crust apart from oxygen and silicon with 8% by weight. It is also the second most heavily used metal in the world after iron/steel. History shows that the worldwide production and consumption of aluminium and its alloys is ever increasing with a recent annual output exceeding 50 million tons [61-64].

The appearance of aluminium ranges from silvery to dull grey depending on the surface roughness. Aluminium is characterised by relatively low density (2.7 g/cm\(^3\) as compared to 7.9 g/cm\(^3\) for common steel) and low melting point. Aluminium and its alloys have an FCC structure, which is stable up to its melting point at 660 °C. Pure aluminium is a strongly electronegative soft, light, and ductile; it possesses a strong affinity for oxygen and has high electrical conductivity. It is widely used for foil and conductor cables. However, alloying with other elements is necessary for it to provide the higher strength necessary for other range of applications [65, 66].

Aluminium alloy in wrought form can be cold worked, thereby bringing changes in its properties. Apart from the high mechanical strength, low density and good corrosion resistance properties that aluminium and its alloys exhibit, there are also a reasonable number of other properties that enhance its wide range of applications both in manufacturing industries and for domestic usage. Some of these properties include its high electrical and thermal conductivity, high strength to weight ratio, formability, recyclability, nonmagnetic and non-sparking properties. These properties, therefore, make aluminium alloys employed in an ever-increasing number of applications varying from structural materials to thin foil packaging [61].

2.3.1 Production of aluminium

Aluminium production was largely unknown until about 200 years ago [63]. The pure form of aluminium does not naturally occur in nature. Several raw materials/minerals are available from which aluminium can be obtained. The most common mineral is bauxite which is primarily a mixture of hydrated Aluminium Oxide (Al\(_2\)O\(_3\)·3H\(_2\)O), Iron Oxide (Fe\(_2\)O\(_3\)) and Silicon Oxide (SiO\(_2\)). Its appearance is usually brick red, flaming red or brown because of the iron oxide. Bauxite supplies are found in tropical and subtropical areas [67].

The aluminium production process can be classified into three stages; bauxite mining, alumina production/raw material purification, and aluminium production.

2.3.1.1 Bauxite mining and purification

Open pit mines are mostly used to mine bauxites. Mining of bauxites requires the use of special equipment to cut one layer after another off the surface with the rock transported for further processing. However, there are places where aluminium ore is mined underground. The bauxite is further processed in plants.
where it is crushed by passing through a grinder, washed off from clay, and dried in preparation for separation of the alumina from the other undesirable components such as impurities associated with red mud [67-69].

2.3.1.2 Alumina production

This stage involves four processes [67]:

i. The crushed washed and dried bauxite is digested with sodium hydroxide at high temperatures and under steam pressure dissolving the alumina in a mixture with undissolved impurities.

ii. This mixture is filtered to extract the impurities, and the clarified alumina solution is conveyed to the precipitator tank.

iii. In the precipitator tank, the hot solution alumina is allowed to cool with the minute addition of aluminium hydroxide to stimulate the precipitation of solid crystals of aluminium hydroxide and sodium hydroxide. The aluminium hydroxide, which is insoluble, settles and is removed from the bottom of the tank.

iv. The separated aluminium hydroxide is washed to remove sodium hydroxide filtrates and decomposed by heating to temperatures above 1000 °C, which drive off excess water. The result is that Alumina (aluminium oxide) emerges as a fine white powder.

2.3.1.3 Aluminium production

Aluminium production is achieved through electrolytic reduction since the separation of aluminium and oxygen (aluminium oxide) requires a high amount of energy. For instance, it requires a temperature of 2015 °C to melt. Figure 2-2 shows the process of producing aluminium in pure form and recycling. In the reduction process, alumina is poured into special reduction cells with molten cryolite at 950 °C. Cryolite, however, has the advantage of stability under process conditions and a density lower than aluminium. This permits freshly formed metal to settle at the bottom of the reduction cell. The mixture is then induced with electric current at 400 kA or higher. This induced current breaks the bond between the aluminium and oxygen atoms resulting in liquid aluminium sinking to the bottom of the reduction cell. The primary aluminium is cast into ingots and dispatched to customers or used in the production of aluminium alloys [67, 69].
2.3.2 Alloying of pure aluminium

Aluminium in pure form exhibits weaknesses due to its lack of strength. In order to find a solution to this flaw and preserving the low density and light weight of aluminium, other elements are added to the pure metal for ductility reduction and strength improvement.

According to the report of the Aluminium Association, alloying of pure aluminium is done in the melting house where the metal is poured into a remelting furnace for alloying and fluxing [71]. Alloying requires thorough mixing of aluminium with other elements in the liquid or molten form. Strong alloys are produced by adding a few other elements, such as copper, zinc, magnesium, silicon, manganese, and lithium. Similarly, additions of minute quantities of chromium, titanium, zirconium, lead, bismuth, nickel are also added. The effects of these alloying elements are evident in the wide areas regarding the application of aluminium alloys. In addition, the strong alloys are further strengthened by heating, cooling and deformation treatments called tempering [67].

The variations in the composition of the alloying elements have produced over 400 internationally registered wrought aluminium and wrought aluminium alloys as well as over two hundred cast aluminium alloys designated by the Aluminium Association with a numerical classification system [72].

2.3.3 Standard designation numbering system for wrought aluminium and aluminium alloys

The wrought aluminium, wrought aluminium alloy and temper designation systems for aluminium were created and maintained by the Aluminium Association and recognised by American National Standard
Institute (ANSI) [71, 73]. In the past, a system was used that lacked sufficient rigour, flexibility, and consistency. Therefore, this outdated system was abandoned and replaced by the current system in the mid-twentieth century [73]. However, this review focuses on the current wrought aluminium and aluminium alloy designation system.

The Wrought Aluminium and Wrought Aluminium Alloy Designation System consists of four numerical digits [72]. However, the system can also include alphabetic prefixes or suffixes. Nevertheless, it generally has four numerical digits as earlier indicated and elaborated further below:

1. The first digit designates the principal or major alloying element of the series starting with a number.
2. The second indicates variations in the original basic alloy. The digit is always a zero (0) for the original composition; a one (1) for the first variation; a two (2) for the second variation and onwards. The variations are normally defined by differences in one or more alloying elements of 0.15 to 0.50% or more, depending on the level of the added element.
3. The third and fourth digits designate the specific alloy within the series. There is no special significance to the values of these digits, and they are not necessarily used in sequence.

The aluminium alloy family is well-known by the digit number and the associated main alloying element(s) as shown in Table 2-1. Despite this, there exist three exceptions:

1. 1000 series family members are commercially pure aluminium or special purity types and therefore do not typically have any purposefully added alloying elements. However, they do have minor impurities which are not removed in case the intended application requires it.
2. The 8000 series family is an “other elements” series containing alloys with rather unusual major alloying elements such as iron and nickel.
3. The 9000 series is undesignated.
Table 2-1: Principal alloying elements in the wrought alloy designation system [73]

<table>
<thead>
<tr>
<th>Alloy series</th>
<th>Principal alloying element</th>
</tr>
</thead>
<tbody>
<tr>
<td>1xxx</td>
<td>Mostly pure aluminium; no major alloying additions</td>
</tr>
<tr>
<td>2xxx</td>
<td>Copper</td>
</tr>
<tr>
<td>3xxx</td>
<td>Manganese</td>
</tr>
<tr>
<td>4xxx</td>
<td>Silicon</td>
</tr>
<tr>
<td>5xxx</td>
<td>Magnesium</td>
</tr>
<tr>
<td>6xxx</td>
<td>Magnesium and silicon</td>
</tr>
<tr>
<td>7xxx</td>
<td>Zinc</td>
</tr>
<tr>
<td>8xxx</td>
<td>Other elements</td>
</tr>
<tr>
<td>9xxx</td>
<td>Undesignated</td>
</tr>
</tbody>
</table>

2.3.4 Classification of wrought aluminium alloys

Wrought aluminium alloys are primarily utilised for the production of wrought products either by hot working or cold working [62, 74]. They can be classified into three groups based on alloying element, purity and thermal treatment. The classifications are discussed in Chapters 2.3.4.1 - 2.3.4.3.

2.3.4.1 Classification based on major alloying elements

Pure aluminium is commonly alloyed to significantly change its properties for structural applications based on the resulting alloying element, namely: copper, manganese, silicon, magnesium, silicon, zinc and other elements such as lithium, nickel, and iron. This classification brings about 2xxx series alloyed majorly with copper, 3xxx series alloyed majorly with manganese, 4xxx series alloyed majorly with silicon, 5xxx series alloyed majorly with magnesium, 6xxx series alloyed majorly with magnesium and silicon, 7xxx series alloyed majorly with zinc and 8xxx series alloyed majorly with other elements, such as lithium and manganese.

2.3.4.2 Classification based on purity

Wrought aluminium alloys are separated into two types based on the purity of aluminium. These are commercially pure aluminium and non-commercially pure aluminium as indicated below.

i. Commercially pure aluminium: The 1xxx series alloys are comprised of 99 % or higher purity aluminium. This series is known for excellent corrosion resistance, and workability, as well as high thermal and electrical conductivity. It is most frequently used for transmission or power grid lines [62].
ii. Non-commercially pure aluminium: In this type, the series alloys consist of 98.99 % or lower purity aluminium. The alloy series and their application are:

a. 2xxx series: The 2xxx series as stated earlier has copper as its principal alloying element with the percentage of pure aluminium less than 99 %. The copper additions range from 0.7 to 6.8%. These alloys possess a good combination of high strength and toughness over a wide range of temperature. However, they do not have an excellent degree of atmospheric corrosion resistance as other aluminium alloys and are usually painted or cladded with high purity alloy for such exposures. Their application is widely known in the aerospace industries, for example, alloy 2024 is the most widely known aircraft alloy [62, 71].

b. 3xxx series: The major alloying element in this series is manganese with the addition of small amounts of magnesium having less than 99 percent aluminium purity. The amount of Manganese addition ranges from 0.05 to 1.8%. The 3xxx series are well known for their moderate strength, good corrosion resistance as well as good workability, has its applications at elevated temperatures such as in heat exchangers, cooking utensils and aluminium beverage cans [62, 71, 75].

c. 4xxx series: These are the aluminium /silicon alloys with silicon addition ranging from 0.6 to 21.5%. They are known to be filler alloys because the addition of silicon reduces their melting point and improves their fluidity when molten. These heat treatable filler alloys are used only when a welded component is to be subjected to post weld thermal treatments such as in fusion welding and brazing. An advantage this series alloy has over others is that it can be used as both a heat treated and non-heat treated alloys. [62, 71, 75]

d. 5xxx series: 5xxx series alloys are the aluminium/ magnesium alloys with magnesium addition ranging from 0.2 to 6.2%. They possess moderate to high strength characteristics, as well as good weldability and resistance to corrosion in the marine environment. These properties lead to a wide variety of applications such as shipbuilding, transportation, pressure vessels, bridges, and buildings. However, alloys in this series with more than 3.0% magnesium are not recommended for elevated temperature service above 339 K since they have the potential for sensitization and susceptibility to stress corrosion cracking. Frequent applications include electronics (5052 aluminium series), marine applications (5083 aluminium series), architectural applications (anodised 5005 aluminium sheets) and beverage can lid (5182 aluminium series) [62, 71, 75].

e. 6xxx series: These are the aluminium/ magnesium-silicon alloys. The magnesium and silicon addition is approximately 1.0%. The 6xxx series alloys are identified with their versatile, heat treatable, highly formable, weldable and having moderately high strength
coupled with excellent corrosion resistance. They are found widely throughout the welding fabrication industry and used predominantly in the form of extrusions and integrated into many structural applications. The most widely used alloy in this series is 6061, which is frequently used in truck and marine frames [62, 71, 75].

f. 7xxx series: Zinc is the primary alloying agent in this aluminium alloy series. Zinc addition ranges from 0.8 to 12.0%. They possess very high strength and often used in high-performance applications such as aircraft, aerospace and competitive sporting equipment [62]. However, they are unsuitable for arc welding and can only be welded with the 5xxx series filler alloys. The most commonly welded alloy in this series is 7005 [71, 75].

g. 8xxx series: These series are commonly called “other aluminium alloy”. The alloying element is other than those used for series 2xxx to 7xxx. Iron and lithium are known to be a major alloying element, giving rise to the different 8xxx series designation. Moreover, iron is basically used to increase strength without significant loss in electrical conductivity, 8017 series is an example. The 8090 series, which has lithium as its primary alloying element, has the exceptionally high strength and stiffness with application in aerospace. General applications of the 8xxx series are found in the heat-sink device, lid stock, aluminium foil (either household or medicinal foil), air-condition foil, bottle cap, radiators as well as structural applications such as aluminium alloy door and window [62, 71, 75].

2.3.4.3 Classification based on thermal treatment

The wrought aluminium alloy can be divided into two groups based on heat treatment [71, 74, 76], as shown in Table 2-2, thereby affecting its mechanical properties, namely:

i. Non-heat treatable alloys: These are alloys in which the mechanical properties are determined by the amount of cold work introduced after the last annealing operation. Generally, 1xxx, 3xxx, 4xxx and 5xxx alloys are non-heat treatable and cannot be strengthened by precipitation hardening. Although, some of the 4xxx alloys can be hardened by heat treatment. This group of alloys cannot be strengthened substantially by thermal treatment since their basic strength is determined or regulated by the alloying content, although their strength can significantly be increased by work-hardening and grain size refinement.

ii. Heat treatable alloys: The heat treatable alloys are capable of being strengthened by suitable thermal treatment usually through precipitation hardening. These alloys can be subjected to solution heat treatment followed by quenching or rapid cooling to improve their mechanical properties. The various elements used in alloying whether singly or in combination display increasing solid solubility in aluminium with increasing temperatures. In heat-treatment, the solid i.e. the alloyed
metal is heated up to a specific point. The alloy elements, called solute, are homogenously distributed with aluminium. This solute creates a solid solution with an aluminium matrix which is subsequently quenched and rapidly cooled freezing the solute atoms in place. The solute atoms consequently combine into a finely distributed precipitate occurring either at room temperature or in a low-temperature furnace operation known as artificial ageing [74]. These alloys include the 2xxx series, the 6xxx series, the 7xxx series and the 8xxx series.

**Table 2-2: Classification of wrought aluminium alloys based on thermal treatment [74]**

<table>
<thead>
<tr>
<th>Wrought alloys</th>
<th>Aluminium alloy series</th>
<th>Atoms in solution</th>
<th>Work hardening</th>
<th>Precipitation hardening</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1xxx</td>
<td></td>
<td></td>
<td></td>
<td>Non-heat treatable alloys</td>
</tr>
<tr>
<td></td>
<td>3xxx 4xxx 5xxx</td>
<td></td>
<td>![star]</td>
<td>![star]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2xxx 6xxx 7xxx 8xxx</td>
<td></td>
<td>![star]</td>
<td>![star]</td>
<td>Heat treatable alloys</td>
</tr>
</tbody>
</table>

**2.3.5 Preparation of wrought aluminium alloys for rolling**

The cast pure aluminium ingots from the electrolytic reduction are usually charged into an alloying furnace where alloying elements are added. These cast ingot materials often carry along with them some unavoidable foreign matter and other non-metallic materials generated as a result of chemical reactions that might have occurred. Therefore, there is the need to prepare the aluminium alloy before being rolled to avoid or cause problems in later operations and impair product quality. The preparation steps include [67, 77]:

i. **Scalping of the rolling ingot**: The surface of a rolling ingot contains oxides formed during the solidification process. These oxides are detrimental to the product, and the ingots are consequently machined in a milling operation to remove the surface layer from the surfaces and sides.

ii. **Pre-heating and homogenising the ingot**: Scalped ingots are initially preheated to ensure that a homogenous structure is created from the cast product which is important for uniformity in the final product. The scraped ingots are heated to a temperature ranging between 500-620 °C. The preheating temperature is commonly regulated for precise homogenization.

iii. **Fluxing and filtration**: Dissolved hydrogen gas in the molten aluminium alloy is derived from airborne water vapour, materials added to the melt, or from furnace walls, tools or anything that
comes in contact with the melt. This dissolved hydrogen is removed by bubbling dry and hydrogen-free gases through the molten aluminium. This process is called “fluxing”, where the hydrogen dissolved in the aluminium diffuses into inert (non-reactive) gases; and it is carried out of the melt by the rising bubbles. It should be noted that foreign particles or inclusions, such as compounds formed as a result of the reaction of the gases with certain impurities, that have escaped the fluxing process or developed afterwards must be removed from the molten aluminium alloy. Filtration is performed to remove these potentially harmful particles – usually by way of deep bed filters mainly used for multiple casts.

iv. **Re-heating to the hot rolling temperature:** The molten aluminium alloy is further heated to a temperature above the recrystallization temperature of the metal, usually above 0.5 melting temperature ($T_m$) of aluminium, before being hot rolled.

### 2.4 Corrosion of aluminium alloys

As earlier mentioned in Section 2.3, aluminium is one of the most produced and used metals globally, second to ferrous metals. Aluminium has good corrosion resistance; and it is one of the reasons for its heavy usage in typical applications, such as in marine applications. Aluminium noble corrosion resistance is advantageous due to the formation of a natural oxide layer, when exposed to the atmosphere. Aluminium’s high affinity with oxygen develops a thin, compact, tightly adhering and protective self-healing film of aluminium oxide that is relatively inert chemically. However, the literature reports evidence of aluminium and its alloys corroding under typical applications. To mention a few. Rao et al. [78] in their literature review on stress-corrosion cracking, confirm that 2xxx, 5xxx and 7xxx aluminium alloys are susceptible to stress-corrosion cracking. Moreover, a review on the corrosion inhibition performance evaluation for aluminium and its alloys in chloride and alkaline solutions by Xhanari and Finsgar [79], confirms evidence of corrosion in aluminium. Further scholarly articles [80-89] reported also indicate that aluminium and its alloys corrode, despite its formation of a natural oxide layer that is chemically inert.

Corrosion is an electrochemical process of redox reactions. It basically involves the release of electrons by the metal; and these are gained by other elements in the corroding solution [90-92]. Corrosion occurs at a rate determined by an equilibrium between opposing electrochemical reactions at the interface between the metal and an electrolyte solution. In analysing corrosion, it must be understood that corrosion processes are caused by the formation of electrochemical cells. The electrochemical reactions in these cells can be categorized into two half-cell reactions. The first is the anodic reaction, in which the metal goes into solution, as an ion, known as oxidation. The other is the cathodic reaction, known as reduction, where the electrons provided by the anode flow through the metal until they reach the cathode, where they can combine with positively charged ions. Both the anodic and cathodic reactions occur simultaneously. When
these two reactions are in equilibrium, the electrons flow from each of the reactions in a balanced way; and no net electron flow occurs [93, 94]. The diagram depicted in Figure 2-3 best explains the anodic and cathodic current components of the corrosion process.

Figure 2-3: Diagram showing anodic and cathodic current components of the corrosion process [93]

The anodic and cathodic reactions in the corrosion of aluminium alloys in natural seawater solution can be expressed as:

For the anodic reaction, the aluminium metal dissolves:

$$\text{Al} \rightarrow \text{Al}^{3+} + 3\text{e}^- \quad (2.1)$$

While in the cathodic reaction, oxygen is reduced:

$$\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^- \quad (2.2)$$

The exposure of aluminium to natural sea water solution relatively dissolves this surface film, leading to the occurrence of dissolution of the metal (that is corrosion), especially under conditions when self-healing cannot occur; thereby bringing about corrosion – either in the form of pitting corrosion, crevice corrosion, inter-granular corrosion, and so forth [95, 96]. This chemical reaction is represented as:

$$2\text{Al} + \text{O}_2 + x\text{H}_2\text{O} \leftrightarrow \text{Al}_2\text{O}_3\cdot x\text{H}_2\text{O} \quad (2.3)$$

The corrosion reaction establishes the presence of rust by either the weight gained or the weight loss in the form of $\text{Al}_2\text{O}_3\cdot x\text{H}_2\text{O}$.

The subsequent subsection will focus on pitting and bimetallic corrosion.
2.4.1 Pitting corrosion

Pitting corrosion is the predominant mode of corrosion in pure aluminium and its alloys. Pitting corrosion is also known as an oxidation-reduction process; and it occurs as a form of localized corrosion on the metal surface, which is usually identified as cavities or holes. Pitting occurs as a result of galvanic reactions between the elements in the metal alloy due to the environmental conditions. Moreover, the literature reports that pitting corrosion tends to take place on passive alloys in the presence of halogen species, such as chlorides, bromides and halogen fluorides. Scholars considered the mode of corrosion by pitting as more dangerous than other modes of corrosion, especially uniform corrosion. This is because it is more difficult to detect, predict and proffer preventive measures for it [97-100].

The pitting-corrosion mechanism is accelerated, as a result of the dissolution of the passivating film and the gradual acidification of the electrolyte caused by its insufficient aeration. The initiation of pits on the metal surface is mostly due to mechanical damage of the passive film by scratches, intermetallic particle inclusions and localized stresses in the form of dislocations emerging on the surface [101].

An example of pitting corrosion is shown in Figure 2-4, revealing pitting attacks on AA5083 and AA1100 aluminium alloys, respectively [102].

![Figure 2-4: Micrographs showing evidence of pitting corrosion in (a) AA5083 and (b) AA1100 [102]](image)

2.4.2 Bimetallic corrosion

Bimetallic corrosion is also known as galvanic corrosion, or dissimilar metal corrosion. Bimetallic corrosion is an accelerated form of corrosion that takes place between two coupled metals with different potentials in electrical contact that are submerged in an electronically conducting corrosive electrolyte. The
mechanism of bimetallic corrosion was pioneered by an Italian physicist, Luigi Galvani, in the eighteenth century. Further work by Sir Humphrey Davy and Michael Faraday engineered the principle for the protection of metallic structures. The electrode potential difference between two coupled dissimilar metals in the same electrolyte is the driving mechanism for galvanic corrosion. The more electronegative metal acts as the anode; while the more electropositive metal acts as the cathode. The current flows from the anode to the cathode accelerates corrosion on the anode metal; while the cathode metal experiences reduced corrosion due to the cathodic protection effect [103]. Reports have shown that the degree of accelerated attack is most severe at the bimetallic joint between the two dissimilar metals; and it decreases further away from the joint [104]. Figure 2-5 depicts typical bimetallic corrosion documented on aluminium plate along the joint with mild steel [105].

![Figure 2-5: Aftermath of bimetallic corrosion on the aluminium plate along the joint with mild steel](image)

2.5 Roll forming

Roll forming is the most widely used forming process, which provides high production and close control of the final product [106]. In a layman’s language, roll forming can be described as a process of forming sheet metals by various kinds of rolls, in order to create a variety of shapes or cross-sections. Many definitions of roll-forming have been observed in the literature [2, 3, 4, 107, 108].

However, Halmos [58] in his book, explained the concept of roll forming as: “To form sheet metal strips along straight, longitudinal, parallel bend lines with multiple pairs of contour rolls, without changing the thickness of the material at room temperature”.

He further explained that there are exceptions in a practical sense. For instance, the products often exit as the roll-formed curve, or in a spiral form; and they have bend lines at 90° to the longitudinal bend line. These bend lines are not always parallel and straight. Also, the thickness of the material is almost always
reduced to the bend lines – especially in thin curved products, in which the outside fibres are thinner than the inside ones. In addition, roll forming is not only achieved at room temperatures, but also at elevated temperatures. Many metals, ferrous and non-ferrous, as well as non-metals, can be roll-formed at a high temperature, such as titanium and plastics [107].

Juneja [109] also recorded that the roll-forming process can be carried out in the hot, warm and cold states in which the temperature of recrystallization differentiates the forming process.

Hot forming occurs at temperatures above the re-crystallization temperature of the metal; were high temperatures reduce the flow stress of metals resulting in low deforming forces. Hot forming is employed for breaking the ingots down into wrought products, such as into blooms and billets, which are in turn rolled to other products like plates and sheets [109-111].

Cold forming refers to the forming at temperatures below the recrystallization temperature of the metal. The material (metal) gets strain-hardened during the process, thereby increasing the hardness and reducing the ductility subsequently. However, warm forming is done at a temperature higher than room temperature, but lower than the recrystallization temperature [109].

In brief, roll forming is a continuous deformation process of forming sheets, strips or coil metal stock into long shapes through a set of forming rolls, which progressively shape the metal until the desired cross section, is produced. The variety of affordable cross sections is unlimited; and it has applications in many industries, such as building, office furniture, appliances, aircraft, and heating, ventilating and air-conditioning industries [112].

Several operations can also be performed during the roll-forming process with the aid of auxiliary equipment, such as pre-notching, punching, embossing, marking, trimming, welding, curving, and die-forming [112].

2.6 Roll-forming mills

The encyclopaedia dictionary of polymers describes the roll-forming mill as an apparatus for mixing a plastic material with compounding ingredients, comprising two horizontal rolls placed close together [113]. Similarly, The Great Soviet encyclopaedia maintains that it is an automated machine that performs both rolling and auxiliary operations for the pressure shaping of metal and other materials between rotating rolls [114].

Therefore, it can be inferred that roll forming mills are basically machines made up of rolls (working or back-up rolls), bearings to support the rolls, gearbox, motor, speed-control devices, hydraulic systems, screw-down mechanisms and mill stand, as well as a mill drive, which plastically deforms the workpiece when passed between the rolls. In other words, a roll-forming mill is an automatic system or line of
machines that perform both rolling and auxiliary operations, such as the transport of the original billet from the stock to the heating furnaces, and the mill rolls which transfer the rolled material from one groove to another. It also turns and transports the metal after rolling; it cuts it into sections, marks or stamps, trims, packs, and conveys the stock of the finished product [111]. A typical laboratory roll-forming mill is shown in Figure 2-6, consisting of four driven rolls in a mill stand with a screw-down [115].

![Figure 2-6: A typical laboratory roll-forming mill [115]](image)

However, improvements in the technology of the mill structure have led to modern rolling-mills that are almost 100 % operated automatically.

### 2.6.1 Classification of roll-forming mills

Despite the fact that, all roll-forming mills apply the same working principle of rolling, they still differ in a variety of ways, for example; they differ regarding the intended use. Furthermore, roll-forming mills are quite complicated; and they are of several types, classified based on the following:

#### 2.6.1.1 Classification based on operating temperature of rolling

Here, the classification of the rolling mills is according to the operating temperature of the metal (workpiece) to be rolled. There are two types, namely; hot-rolling mills and cold-rolling mills, as elaborated on below.
**Hot-rolling mills:** In these mills, the rolling is done above the recrystallization temperature of the workpiece (i.e., > 0.5 melting temperature $T_m$ of the metal). In the course of rolling the workpiece in these mills, the grains which deform throughout the rolling process recrystallize; and they preserve an equiaxed microstructure and prevent the metal from work-hardening; since the residual stresses are negligible. The hot-rolled products from the process are blooms, billets, and slabs, which have very little directionality in the mechanical properties and in the deformation-induced residual stresses.

**Cold-Rolling Mills:** In these mills, the rolling is achieved below the recrystallization temperature of the workpiece (i.e., < 0.5 melting temperature $T_m$ of the metal). Rolling is usually done in these mills with the slab as the input workpiece at room temperature, which increases the strength of the metal through strain-hardening. The cold-rolled products from the process are sheets, strips, and foils, which have a good surface finish; and they hold tighter tolerance when compared with the hot-rolled products [3, 116].

### 2.6.1.2 Classification based on the mill product

Rolling mills are also classified in three ways. The first is categorised by the type of the products, which are:

- **Flat mills**: Plates, sheets and strips that are rolled by these mills.
- **Long product mills**: These mills roll long rounds, rods and shapes.

The second way is classified, based on the nature of the products, which are:

- **Finishing mills**: These mills produce products that are saleable.
- **Semi-finishing mills**: Semi-finished products that need further rolling in the finishing mills are produced in these mills.

The third way is classified based on the products. This method is known as the historical way of classifying rolling mills, by the product they produce after rolling. Under this classification, mills are of the following types: Blooming, cogging and slabbing mills, Billet mills, Rail mills, Shape or structure mills, Merchant-bar mills, SBQ mills, Wire-rod mills, Plate mills, Hot-strip mills, Cold-strip mills, and Universal mills [116].

### 2.6.1.3 Classification based on the rolling process

This is classified on the basis of the operation method of the rolling process, as indicated as follows:

- **Reversing mills**: In reversing mills, the rolling direction changes after each pass. In these mills, the rolls are stopped, reversed, and then brought back up to rolling speed after each pass. In this case, the workpiece moves in the to-and-fro directions [116].

- **Continuous mills**: With regard to these mills, as shown in Figure 2-7, the workpiece to be rolled moves in one direction only; and also all the mill rolls rotate in a single direction only. It involves a number of
stands that progressively reduce the material being rolled until a final shape (specified by the customer) is rolled [106, 116].

Figure 2-7: A continuous mill with four stands [106]

**Semi-continuous mills:** They differ from continuous mills, on the basis that some rolls stand, usually roughing stands, are reversing types; while other rolling stands, usually finishing stands, constitute continuous rolling.

**Tandem mills:** These types of mills exist where rolling is done in one pass, unlike the conventional mill where rolling is achieved in several passes. However, in tandem mills, there are several stands, and reductions take place successively. Figure 2-8 depicts a tandem-rolling mill with two stands. Tandem mills can either be hot- or cold-rolling types; and the number of stands usually, varies from two (2) to eighteen (18) [116].

Figure 2-8: Tandem-rolling mill with two stands [116]

*2.6.1.4 Classification based on stand arrangements*

There are mainly two types, indicated as follows:

**Cross-country mills**- In these types of mills, the centre lines of initial rolling stands are parallel to each other and the workpiece rolled is shifted perpendicular to the rolling directions. A large number of cross country mills are reversing mills.
**Straight-line mills**- In this case, all roll stands have a common centre line and the workpiece being rolled moves only in forward or forward/ backward directions [116].

2.6.1.5 *Classification based on roll configuration*

Classification of mills based on roll configuration is the major types of mills commonly known. The rolling mills are classified based on roll configuration which are:

**Two high mills**- Regarding these mills, the rolling stands have two rolls arranged opposite to each other, that is, one is on top, and the other is at the bottom. Two high mills can either be reversing mill or non-reversing mill (pull-over) types as shown in Figure 2-9 [111]. It is known to be the first and a very common type of rolling mill [117].

![Figure 2-9: Schematic diagram showing two-high mill-reversing and non-reversing types [111]](image)

**Three-high mills**- In these types of mills as shown in Figure 2-10, the rolling stands have three rolls which rotate in one direction. The workpiece is fed in one direction through two of the rolls and then reversed through another pair. The middle roll is common in each feeding. The upper and the lower rolls are driven while the middle roll rotates by friction [111].

![Figure 2-10: Schematic diagram of a three-high mill [111]](image)
Four-high mills- There are four rolls in this situation which are made up of two smaller diameter rolls, usually with lesser strength and rigidity and are supported by two back-up rolls with larger diameters as shown in Figure 2-11 [118]. Four high mills can also be either reversing or non-reversing types.

Cluster mills- In this type of mills, each set of the work rolls is supported by two back-up rolls. These back-up rolls have a further set of backing rolls in the third tier. Sendzimir mill is also having this type of roll configuration as shown in Figure 2-12. Both are used for rolling thin strips of high strength materials and foils [111].

Planetary Mill- This type of mill is characterised by a pair of large heavy rolls, surrounded by a large number of smaller rolls (called planetary rolls) around their circumference. The planetary mill is shown in Figure 2-13. Each planetary roll gives an almost constant reduction to the feed material as it sweeps out of
a circular path between the back-up roll and the feed material. As each pair of planetary rolls ceases to have contact with the workpiece, another pair of rolls makes contact and repeats the reduction process [116].

![Planetary mill diagram](image)

**Figure 2-13: Schematic diagram of a planetary mill [111]**

**2.6.1.6 Classification based on specialised rolling mills**

These rolling mills produce specialised products by combining rolling process with other processes. The major types of mills under this classification are [116]:

- **Ring mills**- used for rolling rings
- **Transverse rolling mills**- used for rolling in transverse direction
- **Pipe mills**- used for producing different type of pipes such as Seamless, ERW, SAW and many others
- **Thread rolling mills**- used for threading of rods or pipes.

**2.7 Cold rolling process**

Accurate description of the cold rolling process is necessary for clarity and a better understanding of the subject under study. Cold rolling is a basic process for producing strip and sheet. The main objective of the process is to reduce the thickness (gauge) of the strip. In addition, it also helps to improve the strength, hardness, surface (finish) quality and formability of the stock metal (stock material). In most cases, the stock material is plates (slab reduced by hot rolled processes). Cold-rolled products have enormous applications that can satisfy human needs. Some of these applications are in automobiles, appliances, furniture and building, as well as general application, for example, radiator tubes, printing, electrical sector, food and drink cans [119].
The cold-rolling process is mainly conducted at room temperatures. The dimensional accuracy of cold rolled products is determined by the cold rolling process, which involves series of stages as described in the next paragraphs.

In the initial stages of rolling, the reduction is high and is usually termed as the breakdown passes also known as high reduction passes. At this initial stage, the strip temperature usually goes high to even 120 – 130 °C, when two or more successive passes with heavy reduction, are fed without allowing any time for the strip to cool down. The high-temperature conditions are adjusted by proper coolant temperature and the rate of flow of coolant to maintain the temperature within 80 °C. Although, on modern fast mills with automatic controls of shape, this limit in terms of temperature is generally exceeded. Subsequent stages involve a low successive reduction in passes.

In the process of rolling, the (stock) material is subjected to high compression and surface shear stresses, which lead to a longitudinal elongation of the grains and consequential breaking and spreading of the heterogeneities in a more uniform pattern. The strains of deformation on the grains can be partially or fully relieved through heat treatment processes. The surface shear stresses are caused due to friction between the roll and the strip, which ultimately is the factor responsible for bite and drawing up of the strip into the roll [119].

In rolling, the width extension is negligible, and thickness reduction results in a proportionate increase in the strip length.

Modern cold rolling mill, which is mostly automated, requires computer control of parameters such as rolling force and strip tension to minimise deviations during rolling, based on measurements of the strip thickness at the entry and delivery sides of the mill.

2.8 Rolling-mill structure

Over time, there have been advances in the design and the specialisation of the structures of the mill. However, modern rolling mills are electrically driven and highly automated mills. The major parts and mechanisms of rolling mills are frequently identical in design, regardless of the variety and functionality differences.

The structures of rolling mill are usually designed to function relatively to the range of production or the technological process, which brought about classifications of rolling mill.

Most importantly, the structures of rolling mill are classified into main apparatus and auxiliary apparatus. The main apparatus is utilised for deforming metal between rotating rollers. It consists of a single line, or of several main lines, each containing three devices types, namely:
i. One or several roll stands, consisting of the rolls, bearings, frames, adjusting gears, plates, leads and mechanism for setting the rolls;

ii. Electric motors for turning the rolls. In reversible mill structure, its electric motor is also reversible and;

iii. Transmission devices from the motors to the rolls, consisting mainly of gear housings, spindles and clutches. A reducer is occasionally placed between the electric motor and the gear housing. However, if each roller has its own electric motor, the transmission only consists of shafts.

Nevertheless, Mills with horizontal rolls are the most popularly used. These are found in two-high, three-high, four-high, or multi-roll mills. Worth noting, is the fact that, mills with vertical rolls are available but not commonly used. Its usage is found in Universal mills and rotary-rolling mills.

Furthermore, the number and arrangement of the roll stands of a rolling mill are determined by the function of the mill, the number of times the metal must pass between the rolls to produce a given section and the assigned output. In addition, rolling speeds vary greatly and depend mainly on the required output of the rolling mill, the range of rolled products and the technological process. The roll bearings operate at very elevated stresses, and the frame of the working stand is very large, which accepts all the forces produced during the rolling operation. In fact, it usually weighs 60-120 tons or more and is manufactured from cast steel. Its installation requires bolting onto a heavy steel foundation plate to a reinforced-concrete foundation. For this reason, the rotation is transmitted to the rolls using universal spindles with Hooke’s joints.

Conversely, the auxiliary apparatus, which mainly carry out other operations, is made up of supporting equipment, namely:

   i. *Ingot buggies*: transfer the metal from the heating apparatus to the mills receiving roller conveyor.

   ii. *Turning devices*: turn the ingot on the roller conveyor.

   iii. *Roller conveyor or transport vehicles*: transport the metal in accordance with the technological process.

   iv. *Manipulators*: move the metal relative to its longitudinal axis.

Other devices include coolers and picklers, unwinders, coilers, shears and saws, straighteners and presses [120]. A typical rolling mill structure without auxiliary apparatus is shown in Figure 2-14.

To sum up, rolling mill structure requires high power outputs and large drive systems evident in its electrical equipment. Likewise, the lubricating systems, which provide for the continuous automatic feed of lubricant to all the operating parts, are usually located in special lower compartments.
2.9 Model of the rolling process

Models of the rolling process are basically mathematical representations showing the theoretical relations of the various rolling parameters, such as the roll force, the torque, the yield strength of the strip and the strip tensions to each other and the operating parameters. In essence, as stipulated by Yun et al. [121], it is a force-balance equation, which recognises that unbalanced lateral direction tension forces cause a resultant change in the rolling force in the vertical direction. Dieter et al. [1], showed many approximate analytical and numerical solutions developed for modelling the rolling process, namely slab methods, slip line field methods, upper bound and lower bound methods, and finite element methods. The slab method, however, is a fundamental method with some assumptions to simplify the analysis of the rolling process. This method is exclusively reviewed subsequently.

2.9.1 Slab analysis of the rolling process

The elementary theory of the free body equilibrium approach, i.e., the slab or force balance method, was first developed by Siebel in 1925 [1]. The technique relies on dividing the workpiece into some finite regions (strips, slabs, disks), the geometry of which depends on the nature of the problem. Each region is placed in force equilibrium. The method usually invokes the Tresca yield criterion and considers the material to be non-hardening (although allowance for work hardening can be made in an approximate manner by using a mean value of yield stress). It also permits an account to be taken of either Coulomb or
constant shearing friction. It should be noted that friction has often been treated as an adjustable parameter
to provide the best correlation between theoretical predictions and experimental results.

Many scholars as recorded by Yun et al. [121] have employed this technique for analysis of the rolling
process. The application of this technique to analyse the direct drawing or extrusion of the strip has been favourable. Therefore, the method can be used to estimate forging loads for quite complex forgings. However, the slab method provides an unrealistic representation of the stress distribution within the
dehorning material because it is only obtained as a one-dimensional distribution. Furthermore, no account
is taken of the inhomogeneity of deformation, temperature, and strain rate effects [1].

Slab analysis of the rolling process is restricted to the case where the length of the roll bite is several times
larger than its thickness. Under these conditions, the horizontal stresses and velocities along any vertical
slice of the roll gap may be assumed constant, a condition generally called “homogenous deformation.”
Also, the analysis is restricted to stable rolling, where it is required that the magnitude of the surface velocity
of the roll be greater than the entry speed of the strip but less than the exit speed of the strip. This ensures
a “neutral plane,” where the velocity of the strips equals the roll surface velocity, to be within the roll gap.
Prior to the neutral plane, the roll travels faster than the strip, and friction tends to draw the strip into the
roll gap. After the neutral plane, the strip moves faster than the roll surface, and the direction of the friction
is reversed.

2.9.2 Dynamic model of rolling process

The dynamic model is also referred to as the quasi-static model of the rolling process. This method
incorporates the dynamic variations of the roll gap to determine the variations of the rolling force, torque,
strip speed, and strip thickness similar to those occurring under steady-state conditions as a result of
dynamic variations in roll gap. Existing dynamic rolling process models have been recorded [121-124].
Yang et al. [125] dynamic model utilises homogenous deformation theory with the relaxation of
assumptions that were earlier generally adopted in the previous models and the inclusion of work roll
flattening effects and changeable friction coefficient. In addition, a linearization process will be applied to
the rolling process model to obtain a linear dynamic model.

As demonstrated in the geometry of roll gap in the rolling process as shown in Figure 2-15. A strip of
thickness $h_1$ enters the gap between the work rolls with velocity $v_1$ and exits with the thickness $h_2$ and
velocity $v_2$. The back tension is $\sigma_1$ at the entry while the front tension $\sigma_2$ is employed at the exit. The radius
of the deformed work roll is $R'$ and the roll peripheral velocity is $v_r$. $h_c$ is the roll gap change rate, and $x_n$ is
the neutral point position. The origin of the coordinate system is the point at which the vertical line that
connects the centre of the bottom and top work rolls intersects the middle plane of the strip.
When the rolls begin to vibrate, the exit plane does not coincide with the centerline of the rolls, and the neutral point position shifts away from the centre of roll gap. Furthermore, the extremely high rolling force in the roll gap leads to the work roll flattening effect. Neglecting this effect significantly reduces the estimate of the actual contact length between the work roll and the strip within the roll gap, leading to an underestimation of the rolling force. Therefore, a model of the work roll-flattening effect which is more proper for practical working conditions may be expressed as [125]:

$$R' = R \left[ 1 + \frac{16(1-v_1^2)f_y}{(\Delta h+\Delta h_c)\pi E_1} \right] \quad (2.4)$$

Where $R$ is radius without work roll flattening effect; $f_y$ is the roll force per width; $\Delta h$ is the screw down amount of work roll; $\Delta h_c$ is the elastic feedback of the strip; $v_1$ is the Poisson’s ration; and $E_1$ is the young modulus of the roll material.

However, it is noted that in the cold-rolling vibration process, it is obviously inappropriate to consider it to be as constant as usual, because of the effect of the rolling lubrication. This brings about a dynamic friction model, which considers both the fluid as well as solid mechanics characteristics. The dynamic friction model can be expressed as:

$$\tau_s = \eta \frac{dv_r}{dy} p = \mu p \quad (2.5)$$

Where $\eta$ is defined as viscosity; $dv_r$ is derivation of the velocity parallel to the friction stress; $\mu$ is friction coefficient, and $p$ is normal rolling force.
As shown in Figure 2-15, the metal flow into the mill is equal to the metal flow out of the mill, which means that it is no longer suitable for the dynamic rolling process. This is because the metal not only moves along the pass line but also moves along the vertical direction [124]. The pressure distribution differential equation along $x$-direction can be expressed as with the von Mises yield criterion:

$$\frac{dp}{dx} \pm \frac{2\mu p}{h} - \frac{1}{h} \frac{d(hK)}{dx} = 0$$  \hspace{1cm} (2.6)

Where, when $x < x_n$, the lower sign should be used; when $x > x_n$, the upper sign should be used; $K$ is defined as resistance to plane deformation.

Since $h$ decreases and $K$ increases when $x$ changes from the entry to the exit of the strip, it can be assumed that the product of $h$ and $K$ is constant. Based on the reasonable derivation, the rolling force per width along $y$-direction with the consideration of boundary conditions can be express as $K_1$ and $K_2$ are the resistance to plane deformation at entry and exit point.

$$f_y = \int_{x_1}^{x_2} \left\{ (K_1 - \sigma_1) \frac{Kh}{k_1 h_1} \exp[\mu(h_1 - h)] \right\} dx + \int_{x_1}^{x_n} \left\{ (K_2 - \sigma_2) \frac{Kh}{k_2 h_2} \exp[\mu(h - h_2)] \right\} dx \hspace{1cm} (2.7)$$

2.9.3 The hydraulic servo system

The hydraulic servo system of rolling mill plays an important role in the stability of the rolling-mill system. Therefore, a well-defined model that includes the full characters of the system is necessary. Tan et al. [126] assume that the system consists of a double-acting, double-ended hydraulic ram with a three-land four-way spool valve.

For an ideal working condition, the load pressure, $P_L$, is expressed as:

$$P_L = P_1 - P_2$$  \hspace{1cm} (2.8)

Since the servo valve is usually working in the vicinity of zero, its operation point is its absolute value of increment, which means that $x_v = \Delta x_v$. Therefore, the linearization form of dynamic valve flow $\Delta Q_L$ is defined as:

$$\Delta Q_L = K_q \Delta x_v - K_c \Delta P_L$$  \hspace{1cm} (2.9)

Where $K_q$ is the factor of amplification flow; $K_c$ is the pressure flow coefficient, and $x_v$ is the displacement of the servo valve.

The hydraulic cylinder flow continuity equation of hydraulic ram is expressed as:

$$Q_L = A_p \frac{dx_v}{dt} + C_{tp} P_L \frac{V_L}{4E_c} \frac{dP_L}{dt}$$ \hspace{1cm} (2.10)
Where $E_e$ is the equivalent elastic modulus of the liquid; $V_t$ is the equivalent volume of the hydraulic cylinder; $x_p$ is the displacement of hydraulic ram; $C_{tp}$ is the total leakage coefficient, and $A_p$ is the effective area of the piston [125].

2.10 Review of the mechanics and the mathematical models of the rolling process

Numerous numerical techniques have been formulated in analyzing material deformation processes [127-130]. Some of the state-of-the-art techniques include finite differences, finite elements, and boundary elements. Each method is peculiar to the others in specific kinds of deformation problems. In this work, the application of the finite-element technique to flat rolling is employed. Advances in research and development have showcased the varieties of mathematical models to describe the rolling process with the optimum aim of improved quality of rolled products, cost-reduction and an increment in the cost-effectiveness.

The flat-rolling process is characterized with changing cross-sections, that is thickness reduction, of a workpiece by compressive forces applied through a counter-rotating set of rolls separated by a fixed distance determined by the operator. The rolling operation can be divided into three phases: the engagement phase, the stationary phase, and the exit phase. In the engagement phase, the work rolls and the workpiece gets in contact, deforming the workpiece elastically. The velocity of the workpiece into the roll gap is achieved as a result of friction between the roll and the workpiece. The transformation from elastic to plastic states takes place in the stationary phase. This phase is characterized by a steady state condition for rolling forces governed by the plastic flow criterion. Figure 2-16 depicts elastic and plastic regions separated by a surface known as the elastic-plastic interface. The strip (workpiece) draws into the roll gap by friction, and a more plastic flow occurs, until finally when the roll pressure is removed at the exit. During the steady state condition, the relative velocities of the roll and the strip change. As the strip moves forward, it gets to a no-slip or neutral point. At this point, the strip exhibits the same velocity as the roll’s surface – with no relative motion occurrence (i.e. $\tau = 0$).

Afterwards, further compression occurs and the strip increases in speed and the friction changes in that direction, thereby retarding the motion. Finally, there is an exit phase, where the strip (workpiece) is unloaded and returns through an elastic state to the original. The exit velocity of the strip is often larger than that of the roll and the difference between the two velocities is determined by the forward slip [130-132].
According to Orowan [134], the fundamental concept of the metal-rolling process is based on the following assumptions:

- The metal is considered to deform plastically during rolling.
- The arc of contact between the rolls and the metal is a part of the circular geometry of the rolls.
- The coefficient of friction is constant in theory; but in reality, the coefficient of friction varies along the arc of contact.
- The metal only extends in the rolling direction; and no or negligible extension in the width of the material occurs.
- The cross-sectional area normal to the rolling direction is not distorted.

### 2.10.1 Geometric relations in the rolling process

Consider that in Figure 2-16, a metal sheet with thickness $h_{in}$ enters between a pair of rolls of radius $R$ moving with a velocity $v_{in}$. It passes through the roll gap and exits with a reduced thickness $h_{out}$ and at a velocity $v_{out}$ with the width of the sheet assumed to remain constant during rolling [135].

The reduction in thickness, known as draft is given as:

$$Draft = h_{in} - h_{out}$$

Therefore, the ratio of thickness reduction, $r$

$$r = \frac{(h_{in} - h_{out})}{h_{in}} = 1 - \frac{h_{out}}{h_{in}} \quad (2.11)$$

Since there is no volume change in the metal volume at a given point per unit time throughout the process, therefore:

$$wh_{in}v_{in} = whv = wh_{out}v_{out} \quad (2.12)$$
where

- $w$ is the width of the sheet metal
- $h_{in}$ is the entry thickness of the sheet metal
- $v_{in}$ is the entry velocity of the sheet metal
- $h_{out}$ is the exit thickness of the sheet metal
- $v_{out}$ is the exit velocity of the sheet metal
- $v$ is the velocity at any thickness $h$ intermediate between $h_{in}$ and $h_{out}$

Because the width of the sheet is assumed to remain constant, i.e. $w_{in} = w_{out}$

Therefore,

$$v_{in}h_{in} = v_{out}h_{out}$$

$$\frac{v_{in}}{v_{out}} = \frac{h_{out}}{h_{in}} \quad (2.13)$$

From equation 2.10, when $h_{in} > h_{out}$ , then $v_{in} < v_{out}$. That is the velocity of the sheet must steadily increase from entry to exit, such that a vertical element in the sheet remains undistorted.

At some section, as explained above in the second paragraph, the velocity of the rolls and the sheet velocity are the same. This point is called the neutral point or the no-slip point. Between the entry section and the neutral point, the sheet moves more slowly than the roll surface; and the frictional force acts in the same direction as the sheet metal into the roll. On the exit section of the neutral point, the sheet moves faster than the roll surface. The direction of the frictional force is then reversed; and it then opposes the motion of the sheet from the rolls.

From the geometry of the arc of contact in Figure 2-16, the projected arc length ($L_p$) can be expressed as:

$$L_p^2 = R^2 - (R - \Delta h)^2$$

$$\therefore \quad L_p = \sqrt{R\Delta h} \quad (2.14)$$

where,

- $\Delta h$ is the draft

2.10.2 Roll-bite condition

For the sheet metal to be drawn by the roll, the frictional force component must be equal to or greater than the horizontal component of the normal force [135].
Expressing this mathematically as,

\[ F \cos \alpha \geq P_r \sin \alpha \]

\[ \frac{F}{P_r} \geq \frac{\sin \alpha}{\cos \alpha} \geq \tan \alpha \]  \hspace{1cm} (2.15)

*From the Law of Friction,*

\[ F = \mu P_r \]

\[ \therefore \mu = \tan \alpha \]  \hspace{1cm} (2.16)

*where,*

- \( F \) is the tangential frictional force
- \( P_r \) is the radial force
- \( \mu \) is the coefficient of friction
- \( \alpha \) is the angle of bite, or the angle of contact

Mathematical models developed so far in the flat rolling process are numerous; and they can be categorized into two groups: conventional and finite element models [130].

### 2.10.3 Neutral/no-slip zone

Determination of the neutral or no-slip zone in the rolling process, as suggested in the literature, is characterized by velocity and normal roll-pressure phenomena. In the latter, Singh [119] reported that the neutral or no-slip zone is significantly identified based on the fact that the normal roll pressure increases and decreases during the rolling process. The normal roll pressure gradually increases up to the neutral plane; and afterwards it gradually decreases towards the point of exit of the workpiece. He further stated that there are possible changes in the position of this neutral point, as a result of the variations in the back-and-forth tensions, and also due to the acceleration and the deceleration of the rolls.

Moreover, the velocity phenomenon explains the neutral or no-slip zone from the viewpoint that during the rolling process, there exists relative sliding between the roll and the workpiece along the arc of contact in the roll bite. At a certain point along the contact length, known as the neutral or no-slip zone, the velocity of the workpiece is equivalent to the velocity of the rolls. The neutral or no-slip zone is depicted in Figure 2-17. To the left of this point, close to the entrance where the workpiece is pulled into the roll gap by friction, the roller moves faster than the workpiece. While, to the right of this point, at the exit were the material is pulled back into the gap, the roller moves more slowly than the workpiece.
In addition, the rolls pull the workpiece into the roll gap during the rolling process due to the presence of frictional force on the workpiece. In short, the frictional force to the left of the neutral zone must be greater than the frictional force to the right [136].

![Figure 2-17: Schematic diagram showing neutral or no-slip zone in the roll bite [136]](image)

**2.10.4 Conventional models**

**Orowan’s Theory**

The traditionally established model of hot and cold flat rolling is owed to Orowan [137]. Orowan developed a comprehensive one-dimensional equation of equilibrium that combines with a yield criterion, the frictional conditions and Hitchcock’s formula (1935) to evaluate the radius of the flattened, but still circular roll contour and an appropriate description of the material’s resistance to deformation [130].

The 1-Dimensional equilibrium-based model is expressed as:

\[
\frac{d(\sigma_x h)}{dx} + p \frac{dh}{dx} \mp 2\mu p = 0 \tag{2.17}
\]

\(\sigma_x\) is the stress in the direction of rolling and is determined relative to the neutral point; \(p\) is the roll pressure.

Shear stress is given as \(\tau = \mu p\) and using Huber-Mises criterion: \(\sigma_x + p = 2k\)

The formulations therefore become:

\[
\frac{dp}{dx} \pm 2\mu \frac{p}{h} = \frac{2k}{h} \frac{dh}{dx} + \frac{d(2k)}{dx} \tag{2.18}
\]

\(k\) is the yield strength under pure shear.

However, the shortcomings of the Orowan model and its variant are concerned with the description of the boundary conditions of the process. This led to refinements of the Orowan model [138]. The aim is to
achieve maximum accuracy and consistency, while using minimum arbitrary assumptions. Orowan’s refined model consists of several modifications made by scientists. Some of these modifications include:

Plastics flow of the rolled strip in the roll gap

Published by Roychoudhury and Lenard (1984): Homogeneous compression and plane-strain conditions are assumed to exist in the plastically flowing strip. An independent variable is chosen to be the direction of rolling, instead of the angular variable around the roll. It is expressed mathematically as:

\[
\frac{d}{dx}\left[ h \left( p - 2k \pm \tau \frac{dy}{dx} \right) \right] = 2 \left( p \frac{dy}{dx} \pm \tau \right)
\]

\[ y = f(x) = ax + b \]

Figure 2-18: Schematic diagram showing cross section of the deformation in the roll-bite [137]

Flattening of the work roll

Michell’s 1990 solution of the biharmonic equation is used to analyse the stress and strain distributions in the work roll.

Michell’s 2D elastic treatment (1990) is mathematically expressed as:

\[
P_r = p \left[ \int_{x_{entry}}^{x_n} \left[ 1 + \mu \frac{dy}{dx} \right] dx + \int_{x_n}^{x_{exit}} \left[ 1 + \mu \frac{dy}{dx} \right] dx + \int_{x_{entry}}^{x_n} \left[ \mu - \frac{dy}{dx} \right] dx + \int_{x_n}^{x_{exit}} \left[ \mu + \frac{dy}{dx} \right] dx \right]
\]

\[
\frac{M}{2} = p \int_{x_{entry}}^{x_n} \left[ x - y \frac{dy}{dx} + \mu \left( y + xy \frac{dy}{dx} \right) \right] dx - p \int_{x_{exit}}^{x_n} \left[ x - y \frac{dy}{dx} - \mu \left( y + x \frac{dy}{dx} \right) \right] dx
\]

where,

\[ x_n, x_{entry} \text{ and } x_{exit} \text{ are the positions on the x-axis at the entry, neutral and exit points.} \]
Other modifications include:

- Elastic compression and unloading of the strip at entry and exit;
- Frictional conditions at the roll-material interface; and,
- Material’s resistance to deformation.

Schey’s and Sim’s models of the rolling process are summarised mathematically as follows:

*For Schey’s Model*

Roll-separating force per unit width; \( P_r \)

\[
P_r = 1.15Q_p \sigma_{fm} L \tag{2.21}
\]

The average flow strength; \( \sigma_{fm}(\text{Pa}) \) is obtained by:

\[
\sigma_{fm} = \frac{1}{\varepsilon_{\text{max}}} \int_0^{\varepsilon_{\text{max}}} \sigma(\varepsilon) d\varepsilon
\]

where,

\( Q_p \) is the pressure intensification factor, which equals \( p / \sigma_{fm} \) and can be obtained by the graph designed by Schey [88].

\( \varepsilon_{\text{max}} \) is the maximum strain.

\( L \) is the contact length of rolling in m.

*For Sim’s Model,*

The roll separating force in N/mm; \( P_r \)

\[
P_r = 2kLQ_p \tag{2.22}
\]

Sim assumed the angles in the roll gap are very small, \( (i.e. \sin \phi = \tan \phi = \phi) \) and the interfacial shear stress is negligible, with sticking friction between the roll and the strip.

Sim’s mathematical expression for pressure intensification factor; \( Q_p \)

\[
Q_p = \left[ \frac{1}{2} \sqrt{\frac{1-r}{r}} \tan^{-1} \sqrt{\frac{r}{1-r}} - \frac{\pi}{4} + \sqrt{\frac{1-r}{r}} \frac{R'}{h_{\text{exit}}} \ln \left( \frac{h_{np}}{h_{\text{exit}}} \right) + \frac{1}{2} \sqrt{\frac{1-r}{r}} \frac{R'}{h_{\text{exit}}} \ln \left( \frac{1-r}{1-r} \right) \right] \tag{2.23}
\]

where,

\( h_{np} \) is the thickness at the neutral point.

\( r \) is the reduction.
2.10.5 Finite element model

Based on the distinctiveness of the rolling processes that comprise a long steady state, two-scale character (metre/millimetre) due to local deformation, and on the practical requirement from industry, several models have been utilized for the mechanical investigation of the strip-rolling processes; such as the slab or force balance methods, upper bound and lower bound approaches, slip line field analyses and the finite-element method.

The finite-element method (FEM) is currently the dominant discretization technique in structural mechanics. The simple flow chart in Figure 2-19 shows the fundamental concepts of FEM. The physical interpretation fundamental concepts of the FEM are the subdivision of the mathematical model into non-overlapping components of simple geometry, known as finite elements. The response of each finite element is expressed in terms of a finite number of degrees of freedom, described as the value of an unknown function(s) at a set of nodal points. The response of the mathematical model is then taken into consideration to be approximated by that of the discrete model obtained by connecting or assembling the collection of all the elements.

Figure 2-19: Simple flow-chart showing the fundamental concepts of the Finite Element Method (FEM)

Construction of structural finite elements is achieved by using formulation techniques. These are powerful techniques for generating finite-element approximations. They include the Rayleigh-Ritz variational method, the energy balance method, the Galerkin method, the Petrov-Galerkin method and other methods of weighted residuals [139]. However, finite element formulations, in ready to use form, are contained in general-purpose Finite Element Analysis (FEA) programs. The general-purpose FEA software packages utilized by engineers in Civil, Mechanical, Structural, Geotechnical and other engineering fields include; ABAQUS, VisualFEA, Autodesk Simulation, ANSYS, COMSOL Multiphysics, SOLIDWORKS, PTC
Creo, DIANA FEA, DEFORM, MSC finite element product software’s and so on. Published work on FEA in the manufacturing process are well-documented [140-151].

2.11 Cold-rolling mill system modelling and simulation

System simulation has been proven over time as an effective tool for reinforcing or verifying analytic solution methodologies and experimentation in manufacturing industries. The existence of computer simulation for industrial processes dates back more than 70 years [152, 153]; and it has since then developed into a powerful industrial tool. Banks et al. [154] clarified that future organizations not utilizing simulation software might be confronted with the challenge to stay afloat in the competitive world. Process simulation is disputably one of the most powerful tools used in the manufacturing industries today, not only because of time and cost reduction, but also for the increase in competitiveness and the profits of industrial companies [154].

Simulation enhances study and the experimentation of the internal interactions of a complex system or sub-system within a complex system. Simulation requires the creation or development of a model that can be manipulated logically to decide how the physical world works. In other words, it is the imitation of a real-world process or system over time. A model, usually a representation of a system, is merely a human construct for better understanding the real-world activity. Mostly, system models for simulation study are mathematical or physical models, developed with the aid of simulation software, such as ABAQUS, ANSYS, and MARC MENTAT.

Simulation is a design process. Maria [155] best described simulation, as “the process of designing a dynamic model of an actual dynamic system for either the purpose of understanding the behaviour of the system or evaluating the various strategies, usually within the limits imposed by criteria, or a set of criteria, for the operation of the system”. The development of a simulation model and the performing of simulation analysis are stepwise. These comprise: problem identification and formulation, collection and processing of real system data, the formulation and development of a model, model validation and so forth.

The modelling of a cold-rolling system is a complex mechanical deformation activity; and the simulation of the system process is non-linear, quasi-static, stochastic and dynamic. Out of the numerous method solution procedures reported in the literature, the Finite Element Method (FEM) is not only the most applicable; but it is also efficient in analyzing the mechanical deformation processes. Finite element simulation of the flat rolling process has been examined by various researchers. For example, Dvorkin et al. [156] used a two-dimensional finite element model (FEM) based on the flow formulation and the pseudo-concentrations technique to investigate many flat-rolling process situations. The correction to slipping
situations and the bending of the rolled plate was one of the significant concentration points of their examination.

Edberg et al. [157] utilized three-dimensional finite-element analysis for computational modelling of the hot-rolling process. Contact forces, deformations, and different friction models were investigated in the rolling process. Likewise, Shangwu et al. [158] developed a three-dimensional simulation approach for the flat-rolling process. In their work, they exploited the combination of the finite element method with the boundary element method to compute the rolling parameters. Jiang et al. [159] were able to quantify the effect of tension on the humps by using an elastic-plastic material model for plane strain finite element simulations. In addition, Jiang et al. [160] conducted a new finite element analysis of the flat rolling process with the focus on the simulation of elastic entry and exit regions in the roll-bite zone.

Furthermore, Dhingra et al. [161] established a 3-D elastoplastic finite element model for the cold-rolling of steel plates. The model was used to predict the behaviour of the material, considering different rolling variables, such as the friction coefficient, the roller diameter, and the initial height plate thickness. Devarajan et al. [162] utilized ABAQUS, a Finite Element Analysis Software, to develop a two-dimensional elastic-plastic finite element model to simulate the effect of cold rolling of thick steel plate with varying roll angular velocities and roll diameters. Shahani et al. [163] used ANSYS, a standard finite element software, to simulate the hot rolling of a strip. Further work by researchers on the finite elements of the flat industrial processes is recorded [164-167].

2.12 Summary

The literature related to this research investigation is presented in this chapter. The history of metals and their usage was first recorded during the Mesolithic age; and they were then used as stone tools and microliths. Increasing knowledge, and the quest for supremacy in power by man, has facilitated the discoveries of more metals that advanced their industrial usage. However, the pre-historic cold-rolling process was first achieved by Leonardo da Vinci in 1480; and it has since then metamorphosed into new automated technologies of sheet metal production over the ages. A further review of aluminium and its alloys starting from its production to the standard designation numbering system by the Aluminium Association was looked into.

A review on the corrosion of aluminium alloy revealed grey research areas on the effect of surface roughness on the corrosion resistance of metals in typical applications. Further reports from the literature confirmed that, there are limited research studies on the characterization of the 8-series family of aluminium alloys, especially when it is mechanically processed by the rolling-mill method. An extensive review on
the roll-forming, roll-forming mills, the cold-rolling process; and the rolling mill structure was also achieved.

On the other hand, previous research on the mathematical modelling and the mechanics of the rolling process was reviewed. The thermal analysis of the cold-rolling process has not been investigated, due to the widespread assumption of its insignificant impact during the rolling process.

The next chapter deliberates the research methodology implemented for the experimental investigation and the cold-rolling system’s modelling and simulation.
CHAPTER 3
RESEARCH METHODOLOGY

3.1 Introduction

Cold-rolling mills are an important part of the production of sheet metal. As earlier mentioned in Chapter 1, the significance of this research work is essential in contributing to solving the challenges faced in the aluminium rolling industry, useful for hands-on engineers or professionals in the rolling industry, and helpful to engineering students in material mechanics, through its research findings. This chapter describes the research design and the approach used to carry out the work in this thesis in a simple and stepwise manner, as shown in the organogram in Figure 3-1. The research approach is classified into Part A and Part B. Part A discusses the experimental approach; while Part B focuses on the cold-rolling process modelling and the simulation approach. The exclusive study of the material behaviour of aluminium 8015-alloy processed by the cold-rolling mill has not been exclusively mapped. Likewise, the thermal analysis of the cold-rolling process. Consequently, the experimental investigation is categorized into metallography testing, mechanical testing, and electrochemical corrosion testing.

The chemical composition of the tested aluminium alloy metal, as well as the cold-rolling process that was applied to the alloy metal, is described. In addition, a sample preparation for each test and the analysis were described. This includes the characterization of the microstructure, a discussion of the tensile test, the hardness test and the electrochemical corrosion-test methods used to determine the behavioural properties of the alloy metal investigated. Furthermore, the methodology for the modelling and simulation of the cold-rolling process and the heat transfer during the mechanical deformation process is elaborated. The simulation of a real-life industrial cold-rolling process of aluminium 8015-alloy was achieved with MSC Marc Mentat, one of the leading FEM softwares.

3.2 Research design and approach

Williamson [168] was able to distinguish between two major traditions of research approach, based on diverse reasoning styles: The interpretivist and the positivist approaches. Unlike the interpretivist approach that requires an inductive reasoning style, the positivist approach adopts deductive reasoning, which is based on the inference of particular instances from the general principles. Here, in this study, the deductive reasoning research approach is structured accordingly.

Figure 3-1 shows the flowchart of the research approach in this study. The present study started by inventing the topic of interest, based on real industrial encounters in the rolling industry, particularly on the
cold rolling of aluminium 8015-alloy. An effort has been made to investigate the evolving microstructural and mechanical properties of the rolled alloy, and to develop simulation models that would address the thermo-mechanical behaviours of the alloy during the cold-rolling process. Hence, the modelling of the cold-rolling process and the characterization of the evolving properties of processed aluminium 8015-alloy were examined. In addition, the electrochemical corrosion analysis of the alloy at varying degrees of surface roughness is also investigated. Preliminary to each research phase, detailed literature is done on the proposed objectives to collect the relevant information and the facts in related works.

The University of Johannesburg library and online resources: specifically ScienceDirect, SpringerLink, AccessEngineering, and Scopus were used. Furthermore, the theoretical framework and the variables were defined. In anticipation to designing the experiments, an industrial visit to the Tower Aluminium Rolling Mill (TARM), Sango-Ota, Nigeria, was conducted. The industrial visit was done to ascertain the reliability of the experimental set-up and the validity of the Finite Element Models’ simulation that has been employed in this study. Afterwards, the experimental routine was designed accordingly to investigate and decipher the behavioural properties of the aluminium 8015-alloy processed by the cold-rolling mill. The findings were collected, evaluated, analysed and validated with industrial measurement.

A thorough discussion followed; and thereafter, the conclusions were inferred from the research findings.
Figure 3-1: Schematic illustration showing the flow-chart of the research approach presented in this study
3.3 Research problems

Multiple research problems have been raised and answered during each phase of this research. The key challenges can be categorized, on the basis of the four major research areas or topics, as indicated:

- **Study of microstructural and mechanical properties of rolled aluminium 8015-alloy processed by the cold-rolling mill**
  - The chemical composition of the aluminium alloy.
  - The extent to which the alloy is cold-worked.
  - The most appropriate approach to investigate the microstructural and mechanical properties of the cold-worked alloy.

- **Electrochemical corrosion study of rolled aluminium 8015-alloy in a natural sea water medium**
  - Utilization of natural sea water electrolyte solution in the corrosion study.
  - Corrosion potential and rate of the hot- and cold-rolled aluminium 8015-alloy in natural sea water.
  - Effect of surface roughness on the rate of corrosion of the rolled alloy in natural sea water.
  - The most appropriate approach to accomplish the corrosion testing, and to investigate the microstructure of the corroded surface.

- **Finite element modelling and simulation of the cold-rolling process of aluminium 8015-alloy**
  - Finite element analysis software acquisition for the real-life industrial cold-rolling process simulation.
  - The geometry, material model and input-rolling parameter needed to develop the finite element model and the simulation of the cold-rolling process.
  - Development of the 2-D and 3-D Finite Element model for the cold-rolling process simulation.

- **Thermo-mechanical finite element modelling and simulation of the cold-rolling process of aluminium 8015-alloy**
  - The most appropriate approach to model and simulate the coupled thermal/structural analysis of the cold-rolling process.
  - The rolling parameters required to achieve the coupled thermal/structural analysis.
  - Industrial visit to Tower Aluminium Rolling Mill, Sango-Ota, Nigeria.
PART A: EXPERIMENTAL INVESTIGATION

3.4 Material

The aluminium 8015-alloy (AA8015) used in this research was obtained from the Tower Aluminium Rolling Mill (TARM) Nigeria Plc, Km 38, Abeokuta Expressway, Sango-Ota, Ogun State, Nigeria. TARM is one of the largest Rolling Mills in West Africa with modern facilities. The casted AA8015 slabs were subjected to a series of processes, which were explained as follows:

i. **Hot-rolling**: Prior to the hot rolling, the AA8015 slabs formed by solidification of a metallic solution of pure aluminium and the alloying elements were fed into the furnace and heated to above recrystallization temperature up to 525 °C. The continuous casting took the molten AA8015 and solidified it with the aid of roll casters into a continuous strip of about 20 mm thickness. The strip was run through a hot mill in tandem; where its thickness (gauge) was reduced successively to 7 mm plate, followed by coiling to the required manufacturing length in one operation.

ii. **Annealing**: The cast, hot-rolled, and coiled AA8015 was left to cool at room temperature for several hours (sometimes more than a day, as stated by the Head of Operation). This process is known as annealing.

iii. **Cold-rolling**: The annealed coiled AA8015 at ambient temperature was loaded onto the uncooler, and rolled to the customers’ required thickness (in this case 1.2 mm) in a Single Stand Reversing 4-Hi Achenbach Cold Rolling Mill (see Appendix A). The hot-rolled plate with 7 mm thickness is heated up to approximately 120 °C (which is below the recrystallization temperature of AA8015). During each pass, thermal equilibrium was maintained at about 70 °C, with large quantities of coolant being poured over the rolls. After attaining the desired customer’s thickness gauge, the strip is removed from the recoiler and cooled down to room temperature for several hours. The cold-rolling pass schedules were four (4) numbers of passes, which were controlled by an experienced operator, using the computer control system unit.

iv. **Table 3-1** shows a detailed description of the 4-high reversing Achenbach cold-rolling mill in TARM, Ota. In addition, non-reversing cold-rolling of annealed coiled AA8015 at ambient temperature was also achieved in six successive reductions in a non-reversing 4-Hi Cold Mill with equipment No. CRM-ALM-355-736-1473/1 (see Appendix A).
Table 3-1: Detailed description of Achenbach 4Hi reversing cold-rolling mill at TARM

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td><em>Single Stand Reversing 4Hi Cold-Rolling Mill</em></td>
</tr>
<tr>
<td><strong>Make</strong></td>
<td>Achenbach</td>
</tr>
<tr>
<td><strong>Strip width</strong></td>
<td>1250 mm</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>485 m / minute</td>
</tr>
<tr>
<td><strong>Inner coil diameter</strong></td>
<td>600 mm</td>
</tr>
<tr>
<td><strong>Outer coil diameter</strong></td>
<td>1520 mm</td>
</tr>
<tr>
<td><strong>Entry thickness</strong></td>
<td>Max. 8 mm</td>
</tr>
<tr>
<td><strong>Exit thickness</strong></td>
<td>Min. 0.20 mm</td>
</tr>
<tr>
<td><strong>Hydraulic System Pressure</strong></td>
<td>40 Bar</td>
</tr>
<tr>
<td><strong>Load Capacity</strong></td>
<td>12000 kN</td>
</tr>
<tr>
<td><strong>Other Information</strong></td>
<td><em>See available photos in Appendix A</em></td>
</tr>
</tbody>
</table>

**Figures 3-2(a) and (b)** show the hot-rolled, and the cold-rolled AA8015 specimen samples obtained from Tower Aluminium Nigeria Plc, with 7 mm and 1.2 mm thicknesses (gauges) respectively. Also, cold rolled AA8015 specimen samples in a non-reversing 4-high mill were obtained. These non-reversing cold rolled AA8015 specimen samples were of reduced thicknesses (gauges) of 6 mm, 5 mm, 4 mm, 3 mm, 2 mm and 1 mm, as shown in **Figures 3-3 (a), (b), (c), (d), (e), and (f)**. The reason was to examine the evolving properties. Each thickness (gauge) is in sizes of 200 mm by 300 mm from the industry.

![Figure 3-2(a)](image1)

![Figure 3-2(b)](image2)

**Figure 3-2: Rolled specimen samples from Tower Aluminium Nigeria Plc: (a) hot rolled specimen sample with 7 mm thickness [Ra = 2.50 µm]; and (b) cold rolled specimen sample with 1.2 mm thickness [Ra = 0.70 µm]**
3.4.1 Material preparation for elemental analysis of rolled AA8015 specimen samples

Hot-rolled and cold-rolled AA8015 specimen samples of all thickness variations were square-cut in dimensions 60 x 60 mm² (as shown in Figure 3-4) and clamped in a vice to ascertain the flatness of the longitudinal surface, causing it to be flatly positioned to avoid any curves, bends, or bows for accurate elemental analysis. Bruker Elemental Optical Emission Spectrometry was used (picture is shown in Appendix A) to determine the QMatrix analysis results of the elemental composition, as stated in Table 3-2, where it was observed that the aluminium metal was 97.77%; while the main alloying element is iron (Fe). Detailed results can be seen in Appendix A.
Figure 3-4: Some pictures showing square-cut AA8015 specimen samples in sizes of 60 x 60 mm²: (a) a hot-rolled specimen sample; and (b) a cold-rolled specimen sample

Table 3-2: Chemical compositions of the AA8015 specimen (weight %)

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight %</td>
<td>0.478</td>
<td>1.338</td>
<td>0.146</td>
<td>0.074</td>
<td>0.035</td>
<td>0.0067</td>
<td>0.072</td>
<td>0.011</td>
<td>balance</td>
</tr>
</tbody>
</table>

3.4.2 Material preparation and procedure for the mechanical, tensile and hardness test experiment of rolled AA8015 specimen samples

Material strength testing, using the tension test practically involves applying an ever-increasing load to a test sample up to the point of failure. Material preparation for the tensile test experiment was carried out on reversing and non-reversing samples for both hot-rolled and the entire cold-rolled specimen samples. All specimen samples were machined, according to the ASTM standard E8/E8M [169] with gauge length of 50 mm and width of 15 mm. A detailed drawing of the machined tensile test specimen samples is shown in Appendix A. Figures 3-5 and 3-6 show some pictures of the machined tensile specimen samples and the experimental set-up of the tensile test correspondingly. The Instron Model 4400 Universal Testing System was used (see Appendix A) with a load size of 100 kN. The loading axis was parallel to the rolling direction. The tensile test was run at room temperature for three specimen samples each for both hot-rolled and cold-rolled samples; and the results were taken to document the observations.

In addition, TH713 Vickers Micro-Hardness Tester was used (see Appendix A) for micro-hardness testing of the specimens. The hardness is a measure of the alloy metal’s resistance to localized plastic deformation evidenced by the size of the indentation. The depth or size of the indentation is a sign of the hardness of the alloy metal. The hardness was measured at 500 g applied load for 15 seconds at more than six various locations on the specimen surface in the rolling direction, with 1 mm intervals, according to ASTM standard E384-16 [170]. The procedure used for the micro-hardness test is detailed stepwise as follows:
1. The specimen was positioned perpendicular to the indenter in the vice.
2. The indenter was lowered until it slightly touched the specimen’s surface.
3. The appropriate load (F = 500 g) was set for the indenter for 15 seconds.
4. The indenter was allowed to penetrate the specimen’s surface.
5. The load was removed; and the indenter was raised from the specimen’s surface.
6. The appropriate parameter, that is the diameter of the indentation, was measured.
7. The hardness value was computed.
8. The above steps were repeated for more than six various locations on the specimen surface with 1mm intervals, and the average was then computed.

Figure 3-5: Machined tensile test specimen samples
A total of twenty (24) tensile specimen samples and eight (8) hardness specimen samples were tested.

3.4.3 Material preparation and procedure for optical metallography examination of rolled AA8015 specimen samples

The approach or method for optical metallography or microstructural examination is step-wise; and it is recorded, as follows according to the ASTM standard E3 [171]:

1. **Cutting of specimen**: The flat position square-cut hot-rolled, and cold-rolled AA8015 specimen samples of all thickness variations. These were further cut transversely and longitudinally in the rolling direction, as depicted in the diagram in Figure 3-7. This was done with a high-quality Struers product cut-off wheel, having a specification of 3820 rpm, 50 m/s, and dimensions of 250 dia. x 1.5 x 32 mm. A 10S25 cut-off wheel was selected; since the material to be cut is soft non-ferrous metals. The cutting was done correctly by following the cutting parameters that include: - the cutting wheel, feed speed, rotational speed, cooling and contact area during the process in an automated Mecatome T300 cutting machine (see Appendix A). This is evident in the smooth cut surface with absolutely no burs, and the cut pieces were cold.
2. Mounting of cut-specimen: The cut pieces, transverse and longitudinal cut-sections, were deemed necessary for mounting; because the pieces were small and of a complicated shape. Hot compression mounting techniques were utilised. PolyFast was used as the resin in a CitoPress -10/20/ø30 mm mounting machine, as shown in Appendix A. The temperature and pressure were set to 180 °C and 25 bar respectively, with the heating and cooling time set to 5 minutes. It was also ensured that the cut pieces were correctly centralised for appropriate edge retention.

3. Grinding of the mounted specimens: The grinding was done on the basis of the adopted laid-down procedures for aluminium alloys [172]. This involved two stages: plane grinding and fine grinding. SiC paper with 320 grit and MD-Largo were used for the surfaces, respectively. Water was used as a lubricant for the plane grinding, with the revolution and load set at 300 rpm and 180 N, respectively. Furthermore, DiaPro Allegro was used as a suspension for the fine grinding with the revolution and load set to 150 rpm and 180 N, respectively. The time for fine-grinding was however set to 4 minutes; while that of plane grinding was until the disappearance of the damage introduced by the cutting was removed, in order to achieve surface flatness.

4. Polishing of mounted specimens: Polishing of the specimen was also done based on the adopted laid-down procedures for aluminium alloys [172]. This entails diamond polishing and oxide polishing. Diamond polishing has to be carried out first until all deformation, and embedded abrasives from grinding have been removed. This was done by setting the time to 3 minutes, load 150 N and revolution 150 rpm, with MD-Mol disc surface and DiaPro Mol suspension. Subsequently, oxide polishing created an almost scratch-free surface by using OP-Chem surface disc with OP-S suspension. The load, revolution and time used were set on 90 N, 150 rpm and 2 minutes, respectively.
5. **Etching of specimen:** Etching, as it is widely known, reveals the microstructure of a metal or alloy by attacking at different rates and areas of different crystal orientation, crystalline imperfections or different composition with the aid of an etchant. The details of the structure revealed by etching are dependent on the etchant used and the process of application [172]. The etchant used for etching AA8015-alloy is Weck’s reagent. A sufficient time of 10 seconds, or a little longer were observed for the etching of the entire specimen; and it was rinsed immediately with water, and subsequently by means of acetone. Pictures of some of the mounted, grinded, polished and etched specimen samples can be seen in Appendix A.

6. **Microscopic examination:** Consequently, after etching of the specimen samples, microstructural investigation was done by using Olympus BX51M Light Optical Microscopy, equipped with an Olympus DP25 digital camera and TESCAN VEGA Scanning Electron Microscope (SEM) equipped with Oxford Energy Dispersion Spectrometry (EDS). Both microscopes and the photographs are shown in Appendix A. It examines the surface morphology of the different specimen samples; and the photo-micrographs were taken to document the observations.

### 3.5 Electrochemical corrosion investigation of rolled AA8015 alloy

#### 3.5.1 Corrosion samples’ preparation, materials and equipment

The hot-rolled and cold-rolled AA8015 alloy specimen samples were prepared for corrosion testing. The chemical composition in weight per cent of the alloy sample is given in Table 3-2. The hot-rolled and cold-rolled AA8015 alloy sample having thickness of 7 mm and 1.2 mm respectively were prepared for corrosion testing, according to the ASTM standard G1-03 [173]. Each of these specimen samples was square-cut by using an automated Mecatome T300 cutting machine embedded with a 10S25 cut-off wheel, following the markings inscribed on the surface having dimensions 10 mm x 10 mm. Afterwards, an insulated copper wire of WALRO FLEX product, sheathed cables with SANS 60227-5, having voltage up to and including 300/500 V for electric power and maximum current of 6 A, was utilized.

The sheathed copper wire was cut into short lengths and adhered to the cut specimen samples by using epoxy glue for connectivity to the potentiostat and tag attachment for specimen identification. Subsequently, the specimen samples with the copper wires stocked on its surfaces were cold-mounted by using EpoFix Resin and hardener, following Struer’s application note for cold-mounting procedures [174]. However, before cold-mounting the adhered sheathed copper wire onto specimen samples were tested by using a multimeter to ascertain its electrical conductivity.

The mounted specimen samples were further grinded by using SiC paper of varying 320, 800 and 1200 grit and diamond polished with the MD-Mol disc surface. The procedure is the same as that explained in Section
3.3.3. Consequently, four (4) different surface conditions of the specimen samples were attained after cleaning with distilled water and acetone. The surface roughness ($R_a$) was determined by using HOMMEL-ETAMIC TURBO WAVE V7.53, a roughness and contour metrology, for each of the surface conditions; and this was reported in Table 4-11.

Figure 3-8 depicts the specimen samples prepared for electrochemical corrosion testing.

![Image of specimen samples](image)

**Figure 3-8**: Pictures showing the preparation of AA8015 alloy samples for electrochemical corrosion testing: (top left) square-shaped corrosion samples cut in 10 mm x 10 mm surface area; (bottom centre) Cut corrosion samples stocked with copper wire before mounting; and (top right) cold-mounted corrosion samples exposed surface area of 100 mm$^2$ after cleaning

The total number of prepared corrosion samples comprised twenty-four (24). Each of the surface conditions described has three (3) samples each. The materials and equipment utilized in the electrochemical corrosion study included:

- Conductive silver paint;
- WALRO FLEX product, sheathed copper wire cables with SANS 60227-5, 300/500 V and 6 A Max.;
- Epoxy glue (Pattex product-liquid steel);
- Natural sea water electrolyte solution;
- Platinum as the counter electrode;
- Silver/Silver Chloride as the reference electrode;
- A multimeter;
- Cutting and Nose-mouth pliers;
- Teflon tape;
- High-precision laboratory balances with 0.0001 accuracy;
- pH meter;
- Gas burner;
- Distilled water;
- Acetone;
- Glass beaker of 250 ml capacity;
- Ivium Compact-Stat Potentiostat;
- EpoFix resin and hardener;
- Cold-mounting apparatus;
- TESCAN VEGA Scanning-Electron Microscope.

3.5.2 Electrochemical corrosion test procedure

Two electrochemical techniques were utilized in determining the corrosion resistance or behaviour of the rolled AA8015 alloy. The potentiodynamic and polarization resistance were used to measure the corrosion rate. The electrochemical experiment was conducted by using an Ivium Compact-Stat Potentiostat computer-controlled with accustomised Ivium software.

Figure 3-9 shows the experimental polarization cell set-up accordingly. All the experiments were conducted with an open glass cell at room temperature. A glass cell containing 200 ml solution was used for each electrochemical experiment.

The open circuit potential (\(E_{oc}\)) measurement of each sample of the rolled AA8015-alloy was determined, according to ASTM standard G69 [175]. The polarization cell set-up for determination of \(E_{oc}\) consist of connections of the working electrode (prepared AA8015 samples) and the reference electrode in natural sea water electrolyte solution (having pH value of 7.04) to the potentiostat. The potential is measured by the potentiostat for each sample tested; as energy between the working electrode and the reference electrode. The silver/silver chloride reference electrode was chosen to give a stable and reproducible potential in the solution. A density and equivalent weight value of 2.70 g/cm\(^3\) and 8.97 g respectively were assigned in the data option of the Ivium software for the AA8015 material constant. A running time of 3600 seconds was allowed to monitor the potential stability, so as to ascertain a steady-state value.

Consequently, the conventional three-electrode polarization cell was utilized for the potentiodynamic and the polarization resistance experiments [176]. A linear potential sweep in the anodic direction was performed at a scan rate of 0.167 mV/s, starting from 250 mV below the \(E_{oc}\) and terminating at 250 mV
above the $E_{oc}$. The output from these experiments yielded polarization curves showing the current response obtained versus the applied potential.

**Figure 3-9: Electrochemical experimental set-up showing an open glass polarization cell**

**PART B: COLD-ROLLING PROCESS MODELLING AND SIMULATION**

**3.6 MSC Marc Mentat**

According to history, Marc is the first commercial, powerful general-purpose non-linear finite element software invented by the MacNeal-Schwendler Corporation established in 1963 by Richard MacNeal and Robert Schwendler. In 1999, the stakeholders voted to change the name of the corporation to MSC Software Corporation. Currently, it is owned by a Swedish Technology Company, Hexagon AB. Mentat is the dedicated pre and post-processor designed for finite element analysis with Marc [177]. Marc has advanced unique material models; and it has the most robust capabilities for contact, large strain, and Multiphysics analysis to solve static and quasi-static non-linear problems. Unlike linear Finite Element Analysis (FEA) methods that rely on simplifying assumptions, Marc has advanced mathematics and finite element technology that enables the users to consistently obtain converged solutions for highly non-linear problems; and to emulate the complex nature of real-world behaviour and mechanical processes.
The above qualities, coupled with the ease of access and training on MSC Marc Mentat enabled this study on modelling and the simulation of the cold-rolling process of AA8015 alloy to be carried out.

3.7 Modelling and simulation of the industrial cold-rolling process of AA8015-alloy

Manufacturers of flat cold-rolled products continually seek to improve their product quality, mill flexibility and productivity. This section will highlight issues in the modelling and simulation of the cold-rolling process of AA8015-alloy. The key technologies involved in the FE modelling of the rolling process include largely: a geometry-and-assembly model, mesh design and optimization, a material model, contact and friction, and boundary conditions.

3.7.1 2-D and 3-D finite element simulation

3.7.1.1 Problem Features

Cold-rolling is performed at relatively low speeds, thereby making the force of inertia insignificant. The cold-rolling process of AA8015-alloy is essentially a time-dependent, quasi-static, and complex non-linear analysis. It involves the plastic deformation of the aluminium alloy subjected to compressive forces between two constantly spinning rolls, the elastic deformation of rolls and sheets, and the mechanical and metallurgical evolution of the rolled alloy. The computer simulation of this process is essential for design reform of rolling mill structure and for the optimization of process parameters to achieve quick identification of hidden problems, to analyze process parameters for effective processing improvements of the mill. The industrial cold-rolling process of AA8015 alloy plate/sheet by using the Achenbach 4-Hi reversible mill is proposed for two-dimensional and three-dimensional FE simulation, using the Marc Mentat 2016.1.0 version FE package.

The simulation of four pass schedules is anticipated. The Achenbach 4-Hi cold mill used in this research has been used for over thirty years in Tower Aluminium Nigeria Plc, Ota, Nigeria; and it is still functioning – as at the time of visiting it in January 2016. See Appendix A for the report of the industrial visit.

3.7.1.2 Geometry description and model

The Achenbach 4-Hi Mill has a roll stand with four parallel rolls with different diameters, arranged vertically one above each other and symmetrically to the neutral rolling plane. The four rolls are basically two Working Rolls (WR) and two Back-up Rolls (BUR) that are placed with their necks into chocks with the roller bearing and hydrostatic sliding bearings accordingly. The vertical rolling force is transmitted through a hydraulic system that acts on the BURs, which then transmit the force to the WR. The two BURs rotate in the opposite direction, as does the WR. Figure 3-10 shows a simple schematic diagram of the four-high stand revealing a prototype geometry of the Achenbach 4-Hi Mill.
Figure 3-10: Schematic diagrammatic representation of the rolling process, showing the roll stack (Work Roll, WR; and Back-up Roll, BUR) [178]

However, for clever simulation to reduce the computational time, a half symmetry and quarter symmetry has been considered for the two-dimensional and the three-dimensional geometric model simulation, respectively, as shown in Figures 3-11(a) and (b). The BUR is not part of the model design; because the industrial input parameters do not involve the action of the rolling force in which it acts on the back-up rolls (BURs).
The geometry was achieved, based on the dimensions of the Achenbach 4-Hi Mill computed from the Aluminium Rolling Mill Industry, Ota; such that the WR diameter is 400 mm, the BUR diameter is 1000 mm, WR length, 2500 mm and plate width, 1250 mm as measured. The thickness of the plate/sheet varies depending on the number of pass/ schedule pass/ per cent cold work, as shown in Table 3-3. However, a plate length of 100 mm and 50 mm is assumed for the two-dimensional and the three-dimensional model, respectively, in order to reduce the number of elements and nodes, thereby also reducing the time needed for computation. Due to symmetrical conditions, only a quarter of the plate/ sheet is analysed for the three-dimensional model; and a half of the plate/sheet for the two-dimensional model.

It is important to state that the two-dimensional model is assigned with a geometric thickness of the plate/sheet width and top work roll as a rigid analytical curve. The top work roll (WR) is modelled as a
rigid analytical body; and the plate/sheet; these are modelled as deformable bodies. Moreover, the top work roll in the three-dimensional model is constructed as 3-D surfaces.

3.7.1.3 Mesh design and optimization
The mesh design and optimization requires selection of element type, mesh quality check, element size determination and mesh convergence study. In Figure 3-11, the FE models show that the rolls need not to be meshed; because they are modelled as rigid analytical bodies; and they have a rigid surface for the two-dimensional and three-dimensional FE models, respectively. The half plate/sheet and the quarter plate/sheet were meshed. In the two-dimensional FE model, the plate/sheet is meshed by the second-order isoparametric, two-dimensional four-node arbitrary quadrilateral element for plane stress. This element type in MSC Marc is a plain strain full integration element type 11. While in the three-dimensional FE model, eight-node, an isoparametric arbitrary hexahedral element is used in meshing the quarter plate/sheet. This element type in MSC Marc is a full integration element type 7. A detailed number of nodes and elements in each FE models for each pass schedule is given in Table 3-3. The aspect ratio of the elements is approximately 100%; although in the 3-D models, the width direction is about 3.5 times longer than they are in the rolling direction.

The mesh size is optimized by performing a mesh convergence study, in which the AA8015-alloy cold rolling process simulation for both FE models is done with different levels of refinement of the mesh – until when further mesh refinement produces a negligible change in the process parameter solution. At this point, the mesh is said to be converged.

Table 3-3: Material data and mesh density

<table>
<thead>
<tr>
<th>Entry thickness of plate/sheet (mm)</th>
<th>Exit thickness of plate/sheet (mm)</th>
<th>Yield Strength (MPa) “before rolling”</th>
<th>Rotational speed of driving work roll (rad/s)</th>
<th>Mesh density for 2-D models</th>
<th>Mesh density for 3-D models</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of nodes</td>
<td>No. of elements</td>
<td>No. of nodes</td>
<td>No. of elements</td>
<td>No. of elements</td>
<td></td>
</tr>
<tr>
<td>7.0</td>
<td>4.5</td>
<td>71.9</td>
<td>2.20</td>
<td>3157</td>
<td>2860</td>
</tr>
<tr>
<td>4.5</td>
<td>3.4</td>
<td>146.0</td>
<td>3.20</td>
<td>4906</td>
<td>4450</td>
</tr>
<tr>
<td>3.4</td>
<td>2.4</td>
<td>197.5</td>
<td>4.25</td>
<td>6479</td>
<td>5880</td>
</tr>
<tr>
<td>2.4</td>
<td>1.64</td>
<td>209.0</td>
<td>7.25</td>
<td>9174</td>
<td>8330</td>
</tr>
</tbody>
</table>

3.7.1.4 Material model
Material models are necessary, in order to eliminate trial-and-error loops during simulation. The knowledge gained from this research reveals that the modelling of material behaviour is the most important factor in the rolling simulation, whether hot or cold rolling. Its effect produces a closer correlation to the exact
solution than the friction models. AA8015-alloy material is utilized in this work. The account of the path-dependent behaviour that the AA8015-alloy material follows, as it is cold-rolled shows an elastic deformation; as it enters and exits the roll gap and a plastic deformation, as the alloy undergoes the bulk of the deformation process. Hence, the use of elastic-plastic flow formulation. The elastoplastic solid formulation takes account of the elastic contribution to the total strain rate; and it provides the possibility of evaluating the residual stresses in the sheet after rolling.

This solid formulation is based on the Prandtl-Reuss representation of the flow rule in conjunction with the Von Mises yield criterion, with isotropic hardening to initiate yielding; and it is usually used for the cold-rolling process.

The variable hardening behaviour of the AA8015-alloy is accounted for by subjecting the hot-rolled alloy of 7 mm plate thickness to be cold-rolled and a subsequent three consecutive reduction pass schedule of cold-rolled alloys, obtained from the Aluminium Rolling Mill for tensile testing at an ambient temperature, according to the ASTM standard by utilizing an Instron Model 4400 Universal Testing System [179]. This is because for each pass, the AA8015 alloy sheet changes in its mechanical and metallurgical attributes. The resulting effective stress-effective plastic strain, in Table 3-4, was computed and validated by using an inverse modelling technique [180] from the obtained tensile test results for each pass schedule. The inverse modelling technique is an inverse finite element procedure that aims to determine the true stress-strain curve in an iterative manner from the FE simulation of the tensile test of the AA8015-alloy.

The AA8015 aluminium alloy is well-thought-out to have a density, $\rho = 2700\text{kgm}^{-3}$; and Poisson’s ratio, $\nu = 0.32$. Young’s Modulus, $E = 59\text{ GPa}$ and $62\text{ GPa}$ for the hot- and cold-rolled alloy respectively; and in Table 3-3 the corresponding yield strengths are shown.
Table 3-4: AA8015-alloy variable hardening model

<table>
<thead>
<tr>
<th>PASS 1</th>
<th>PASS 2</th>
<th>PASS 3</th>
<th>PASS 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective plastic strain</td>
<td>Effective stress (MPa)</td>
<td>Effective plastic strain</td>
<td>Effective stress (MPa)</td>
</tr>
<tr>
<td>0</td>
<td>71.9389</td>
<td>0</td>
<td>146</td>
</tr>
<tr>
<td>0.00381</td>
<td>72.4173</td>
<td>0.00901</td>
<td>150.96</td>
</tr>
<tr>
<td>0.008661</td>
<td>74.1521</td>
<td>0.0165</td>
<td>155.92</td>
</tr>
<tr>
<td>0.015767</td>
<td>76.7325</td>
<td>0.0275</td>
<td>160.88</td>
</tr>
<tr>
<td>0.020215</td>
<td>78.4449</td>
<td>0.034375</td>
<td>163.36</td>
</tr>
<tr>
<td>0.037432</td>
<td>84.7192</td>
<td>0.04125</td>
<td>165.84</td>
</tr>
<tr>
<td>0.049262</td>
<td>87.6129</td>
<td>0.055</td>
<td>170.155</td>
</tr>
<tr>
<td>0.05961</td>
<td>90.5898</td>
<td>0.059125</td>
<td>170.8</td>
</tr>
<tr>
<td>0.074532</td>
<td>94.2154</td>
<td>0.075625</td>
<td>175.76</td>
</tr>
<tr>
<td>0.096896</td>
<td>98.2933</td>
<td>0.0825</td>
<td>177.496</td>
</tr>
<tr>
<td>0.136699</td>
<td>105.465</td>
<td>0.099</td>
<td>180.72</td>
</tr>
<tr>
<td>0.161373</td>
<td>108.689</td>
<td>0.11</td>
<td>182.753</td>
</tr>
<tr>
<td>0.176575</td>
<td>110.777</td>
<td>0.127875</td>
<td>185.68</td>
</tr>
<tr>
<td>0.222984</td>
<td>116.563</td>
<td>0.1375</td>
<td>187.116</td>
</tr>
<tr>
<td>0.268036</td>
<td>121.379</td>
<td>0.165</td>
<td>189.995</td>
</tr>
<tr>
<td>0.354664</td>
<td>130.661</td>
<td>0.17325</td>
<td>190.64</td>
</tr>
<tr>
<td>0.39101</td>
<td>134.422</td>
<td>0.1925</td>
<td>192.424</td>
</tr>
<tr>
<td>0.4124</td>
<td>136.221</td>
<td>0.22</td>
<td>194.112</td>
</tr>
<tr>
<td>0.43111</td>
<td>137.611</td>
<td>0.2475</td>
<td>194.856</td>
</tr>
<tr>
<td>0.44</td>
<td>138.61</td>
<td>0.275</td>
<td>195.6</td>
</tr>
</tbody>
</table>

### 3.7.1.5 Contact and friction model for 2-D and 3-D finite element simulation

The contact and friction mechanisms are non-linear boundary value problems in the cold-rolling process due to the heat arising from the work of the friction forces on the contact surface. In cold-rolling, the contact problem mechanism and especially the friction mechanism are extremely complicated; and yet, to be fully understood.

It is very important to make a brief theoretical explanation of these mechanisms. Contact problems are characterised by two important phenomena namely: the roll gap opening/closing and friction. The roll gap describes the contact (gap closed) and the separation (gap open) conditions of the two work rolls in contact with the plate/sheet. Friction influences the interface relations of the work rolls and the plate/sheet in contact. The surface interface characteristics, such as surface roughness, temperature, normal stress and relative velocity are the actual physics of friction that continue to be a topic of research.

In the two-dimensional and three-dimensional FE models in this work, a deformable-rigid contact is utilized. The deformable plate/sheet makes contact with the rigid analytical curve and the rigid 3-D surfaces,
respectively. In deformable-rigid contact, a target node on the deformable body has no constraint; while contact does not occur. Once contact is detected, the degrees of freedom are transformed to a local system; and a constraint is imposed.

Due to symmetry, a contact pair is defined between the upper roll and the AA8015-alloy plate/sheet in the FE models. The set-up of the contact parameters of the deformable-rigid contact in MSC Marc is as follows:

**Contact detection and contact type**
The Marc default settings of the contact distance tolerance and the Bias factor were chosen, and given as 0 and 0.95 respectively. A touching contact type was selected because in the rolling process, a touching and not glued interaction occurs. A separation force or stress of zero was assigned.

**Contact interaction friction parameters**
The interaction between the contact bodies – the steel–made upper work roll and the AA8015 plate/sheet at the interface creates friction in the operation. Yingjian Liu in his doctoral experimental research, worked on the friction coefficient of measurement in the cold rolling of aluminium alloy 6060-T5 with a steel work roll by using two methods. Friction-coefficient measured values from the two methods were found to be in close proximity to each other. The values are within the range of 0.075 and 0.106 [181]. Based on this finding, a friction coefficient of 0.106 and a friction stress limit of $1 \times 10^{20}$ were used.

**Contact-solution control and convergence**
The Marc segment-to-segment contact algorithm was used with the Coulomb Bilinear (displacement) friction type and the finite sliding model. Moreover, a Full Newton-Ralphson iterative procedure and a large-strain non-linear procedure with implicit transient operator analysis were selected. Subsequently, residual or displacement load-case convergence criteria with a relative tolerance of 0.001 were designated.

**3.7.1.6 Boundary conditions for 2-D and 3-D finite element simulation**
To obtain a solution for stress, strain, strain-rate and velocity within the rolled plate/sheet, appropriate boundary and initial conditions were described, as depicted in Figures 3-12 and 3-13 for the two-dimensional and three-dimensional FE models, respectively. Symmetry constraint is applied to the axial symmetrical plane of the plate/sheet perpendicular to the direction of rolling (i.e., the y-component of displacement is fixed to zero displacement), to accomplish symmetric deformation in the axial direction. In addition to symmetrical constraint being applied for the half and quarter symmetry FE models, an initial fixed displacement condition with a displacement of 0.00571 mm in the x-axis direction is fixed to the nodes on the left edge/face of the plate/sheet.
3.7.2 Coupled thermo-mechanical 2-D finite element simulation of the cold-rolling process of AA8015-alloy

3.7.2.1 Problem features and synopsis of the industrial cold-rolling process
Thermo-mechanical analysis is a thermal-structural analysis technique that is used in studying properties of materials, as they change with temperature. Analysing coupled heat-transfer problems in the cold-rolling process using FEA is not common; due to the widespread assumption of insignificant impact during the rolling process. In this work, a coupled thermo-mechanical finite element simulation model is deliberated by using the MSC Marc Mentat. A two-dimensional, thermo-mechanical, transient, non-linear rolling
model is proposed for this study. Two case studies: deformable-rigid and deformable-deformable contact algorithm were recommended. Likewise, the rolling simulations of four pass schedules are anticipated. The coupled thermo-mechanical study of the cold rolling process of AA8015-alloy is essential in mill design for determining the thermo-mechanical behaviour of the work roll and the AA8015-alloy plate/sheet during the cold-rolling process.

Furthermore, a synopsis of the cold-rolling process of AA8015-alloy accomplished at Tower Aluminium rolling mill, Sango-Ota, Nigeria, in a Single Stand Reversing 4-Hi Achenbach Cold Rolling Mill with maximum rolling force of 12000 kN is necessary to aid in a better understanding. The cold-rolling was performed at different temperatures below the recrystallization temperature of the work piece. The hot rolled AA8015 aluminium alloy at an industrial ambient temperature of about 30 °C was first preheated to an approximate temperature of 120 °C, before being fed into the cold-rolling mill. The high initial reduction pass causes the temperature to increase. This is due to the conversion of the mechanical plastic work and the friction energy that is converted to heat energy. Cooling down with a high amount of oil-based lubricant ensures thermal equilibrium; and it maintains the exit temperature of the cold-rolled AA8015-alloy to about 70 °C in the first pass. Due to the reversing design of the mill, subsequent reversing rolling passes of AA8015-alloy metal are fed at an approximate temperature of 70 °C.

3.7.2.2 Geometry description and FE model
Two-dimensional finite element (FE) models were developed to analyze the thermo-mechanical behaviour of the AA8015-alloy in the cold-rolling process, one using deformable-rigid contact and the other using deformable-deformable contact. Both taking account of the heat transfer by conduction from the AA8015-alloy plate/sheet to the rolls; however, for the deformable-rigid contact, heat transfer to the rolls was not determined; because it cannot be recovered. The two-dimensional FE models consist of two basic parts: the circular upper roll and the rectangular shaped AA8015-alloy plate/sheet work piece, as shown in Figures 3-14 and 3-15.

For the 2-D plane-strain simulations, a half-symmetry model was utilized with the plate/sheets modelled as deformable bodies, and the upper roll modelled as a rigid body for deformable-rigid contact. Whereas, for deformable-deformable contact, the upper roll is modelled as a deformable body, having a circular hollow shape of 5 mm thickness. Both contact types have an upper work roll diameter of 400 mm. The plate had an initial cross-section of 100 x 1250 x 7 mm; and the thickness was reduced by 36 % cold work at the first pass. In subsequent passes, shown in Table 3-5, apart from the sheet length fixed to 100 mm, the operator varied entry thickness and/or the per cent cold work based on the pass-schedule design.
3.7.2.3 Determination of coefficient of friction model

Friction in the contact zone is a non-linear force. Prihod’ko et al. [182] confirm that the friction forces between the work rolls and rolled material have a non-linear relation with the normal force. Based on the experimental studies from a practical condition of the cold-rolling of Aluminium alloy 6060-T5 by Tieu and Liu [183], the coefficient of friction model utilized in this work was conceived. In his rolling experiment, the sensor-roll method was used in determining the coefficient of friction; and the rolling speed was varied from 0.31 rad/s to 6.81 rad/s for the same thickness reduction of about 38%.

This resulted in a friction coefficient range of values between 0.1374 and 0.0757. These results confirm earlier work by Al-Salehi et al. [184] in which typical coefficient of friction between 0.1 and 0.06 was obtained. Based on these findings, with the inclusive statement that the average coefficient of friction decreases with increasing rolling speed; and assuming the negligible effect on the thickness reduction, the friction coefficient in Table 3-5, was chosen for the finite element (FE) simulation of each rolling pass.
3.7.2.4 Determination of thermal contact conductance coefficient

To a certain extent, there exist major difficulties in the choice of the thermal contact conductance coefficient in thermal fields in the strip and rolls [185]. The temperature drop at the interface between the contacting surfaces is caused by the energy exchange, which takes place from a hotter body to a colder one, especially when two solids come in contact [186]. However, the thermal contact conductance coefficient (hc) is not only dependent on the material conductivity behaviour of the two contact bodies, but also on the surface roughness or waviness. In this work, steel to aluminium body contact is established. Timothy et al. [187] obtained a thermal contact conductance coefficient of 15 kW/m² °C in their quest to examine the temperature distribution in the laboratory rolling of AA5083, utilizing subsurface thermocouples.

However, Pietrzyk et al. [188] in their findings, revealed a value range of 18.5 and 21.5 kW/m² °C for the warm rolling, thereby satisfying the use of 15 kW/m² °C for the thermal contact conductance coefficient in the FE model simulation.

3.7.2.5 Material model, mesh design and optimization

The rolls were modelled as 9Cr2Mo steel material for the deformable-deformable contact; and the reference-rolled material was modelled as AA8015 aluminium alloy. The solid formations of the finite element simulation are based on Von Mises yield criterion, and the associated flow rule for the elastic-plastic materials. The variable hardening model of the AA8015-alloy metal for each successive roll pass given in Table 3-4 was plotted. See Figure 3-16. Plane strain four-nodes, isoparametric, and arbitrary quadrilateral elements with heat transfer application were used in the two-dimensional FE models with an aspect ratio of 100%.

A detailed number of nodes and elements in each coupled thermo-mechanical FE model for each pass schedule was also given in Table 3-5. The thermal and mechanical properties are presented in Table 3-6. Likewise, for mesh optimization, a mesh-convergence study is performed in the FE models at different refinement levels of the mesh. However, in the deformable to deformable contact algorithm, the roll mesh elements used have a similar size as the plate/sheet mesh elements at the rolls circumference/surface, in order to enable convergence.
Table 3-5: Material data and mesh density

<table>
<thead>
<tr>
<th>Pass Schedules</th>
<th>Percent cold work</th>
<th>Entry thickness of plate/sheet (mm)</th>
<th>Coefficient of Friction</th>
<th>Rotational speed of driving work roll (rad/s)</th>
<th>Mesh density for deformable-rigid contact 2-D models</th>
<th>Mesh density for deformable-deformable contact 2-D models</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No. of nodes</td>
<td>No. of elements</td>
</tr>
<tr>
<td>Pass 1</td>
<td>36%</td>
<td>7</td>
<td>0.094</td>
<td>2.2</td>
<td>3157</td>
<td>2860</td>
</tr>
<tr>
<td>Pass 2</td>
<td>24%</td>
<td>4.5</td>
<td>0.087</td>
<td>3.2</td>
<td>4906</td>
<td>4450</td>
</tr>
<tr>
<td>Pass 3</td>
<td>29%</td>
<td>3.4</td>
<td>0.080</td>
<td>4.25</td>
<td>6479</td>
<td>5880</td>
</tr>
<tr>
<td>Pass 4</td>
<td>32%</td>
<td>2.4</td>
<td>0.06</td>
<td>7.25</td>
<td>9174</td>
<td>8330</td>
</tr>
</tbody>
</table>

Figure 3-16: Plasticity curves for hot- and cold- rolled AA8015-alloy specimens

Table 3-6: Thermal and mechanical properties of AA8015-alloy metal and work roll

<table>
<thead>
<tr>
<th>Properties</th>
<th>AA8015 feed stock</th>
<th>9Cr2Mo Steel Roller</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass density</td>
<td>2700</td>
<td>7833</td>
<td>Kg m⁻³</td>
</tr>
<tr>
<td>Elastic modulus (HR/CR)</td>
<td>59/62</td>
<td>210</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.32</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>23.6</td>
<td>11</td>
<td>ppm K⁻¹</td>
</tr>
<tr>
<td>Thermal conductivity (at 70 °C &amp; 120 °C) for Al</td>
<td>240</td>
<td>26</td>
<td>W m⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>910</td>
<td>460</td>
<td>J kg⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.09</td>
<td>0.8</td>
<td>-</td>
</tr>
</tbody>
</table>

3.7.2.6 Contact and friction model for coupled thermo-mechanical finite element simulation

The contacts problem is described as deformable-rigid and deformable-deformable contacts, as previously mentioned. The analysis of contact behaviour was based on the interaction of the touching contact bodies. This ensures prescription of coefficients of friction between surfaces for each pass schedule, as given in Table 3-5. A contact thermal transfer coefficient of 15 kW/m² °C between steel-to-aluminium bodies is
used. A segment-to-segment contact procedure was utilized. In addition, the residual force or the displacement convergence criterion with a tolerance of 0.00001 was designated.

The initial temperature of the AA8015-alloy plate was set to 120 °C in the first pass and to 70 °C in the subsequent pass schedules, due to the use of a coolant. Due to the thermo-mechanical interactions, a transient dynamic analysis is utilized.

3.7.2.7 Boundary conditions for coupled thermo-mechanical finite element simulation

The boundary conditions defined in the two-dimensional FE models are replicas of the industrial rolling conditions. Figures 3-17 and 3-18 show the initial and boundary conditions generated in the deformable-rigid and deformable-deformable contact algorithm FE models, respectively. Likewise, symmetry constraints are applied for the half symmetry models, with an initial fixed displacement condition having a displacement of 0.00571 mm in the x-axis direction, fixed to the nodes on the left edge/face of the plate/sheet. The initial temperature of the deformable plate and the work roll are prescribed to be at an ambient temperature of 25°C.

Other conditions that are considered are:

- **Plastic heat generation**: Plastic deformation and friction make an enormous contribution to heat generation. Farren et al. [189] confirmed that an approximation of 90 % of the mechanical energy of deformation is converted into heat. While the remaining 10 % mechanical energy is used in dislocation. Therefore, a plastic heat generation factor of 0.9 (90%) is utilized.

- **Film convection**: It is assumed that free convection to the environment at the plate surface is taking place. Therefore, a film air-convection coefficient, \( h = 50 \text{ } W/\text{m}^2\text{K} \) and 0.09 emissivity is prescribed.

---

**Figure 3-17**: 2-D coupled thermo-mechanical FE model representation for deformable-rigid contact before the start of rolling showing boundary conditions on the deformable plate/sheet
3.8 Summary

The research procedure has been adequately presented and discussed for the experimental studies: mechanical testing, metallography testing and electrochemical corrosion testing; and Finite Element (FE) modelling and simulation of the cold-rolling process of aluminium 8015-alloy. Consequently, the material under investigation was obtained from Tower Aluminium Rolling Mill (TARM), Sango-Ota, Nigeria. The report of the industrial visit is given in Appendix A. The subsequent chapter presents the findings, which will be discussed appropriately.
CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The findings of the experimental studies: mechanical, metallography and electrochemical corrosion tests; and the cold-rolling process modelling and simulation are presented and discussed in this chapter. Likewise, the results are classified into Part A and Part B, as it is done in Chapter three (3). Prior to presenting and discussing the experimental results in Part A, it is important to state that the raw data from the experimental testings were further analysed. Some of the analysis done is summarized and stated as follows:

The tensile test was accomplished to obtain the stress-strain behaviour, the yield strength, the ultimate tensile strength, the modulus of elasticity and the amount of ductility. Stress-strain diagrams were plotted from the data collected from the Instron Model 4400 Universal Testing System for all specimen samples. The yield strength was found with 0.2 % amount of offset while the tensile strength was determined by the maximum value of stress applied. Meanwhile, the amount of ductility in the per cent elongation was calculated by using equation 4.1[190]; and the modulus of elasticity was calculated by finding the slope of the stress-strain graphs.

\[ \% \text{Elongation} = \frac{l_f - l_o}{l_o} \quad 4.1 \]

Where \(l_f\) is the fracture length and \(l_o\) is the original gauge length of the tensile specimen.

Moreover, the Vickers hardness test utilizes a diamond pyramid-shaped indenter that is ground in the form of a squared pyramid with an angle of 136° between the faces, and the depth of indentation is about 1/7 of the resulting impression’s diagonal length. The Vickers hardness number designated by HV was calculated by using equation 4.2 [191], and the average values were computed and presented in Table 4-9.

\[ HV = \frac{1.854 P}{d_i^2} \quad 4.2 \]

Where \(P\) is the load in gf and \(d_i\) is the arithmetic mean of the two diagonals of the indentation, \(D_1\) and \(D_2\) in mm.

In addition, in the finite element simulation of the AA8015-alloy rolling process, there are a reasonable number of rolling process parameters that can be considered. However, the contact-friction force distribution, the plastic strain rate distribution, the Von Mises stress distribution, the normal and shear stress distribution, the roll separating force and the roll torque from the 2-D and 3-D FE model simulations were designated for analysis. Inclusive in the coupled thermo-mechanical FE models are the heat-flux distribution and the temperature distribution. The highest interferences were selected for the discussion.
PART A: RESULTS AND DISCUSSION OF EXPERIMENTAL INVESTIGATION

4.2 Mechanical tensile and hardness test results

4.2.1 Mechanical tensile test measurements for hot-rolled AA8015 specimen samples

The mechanical tensile test measurements result showing the stress-strain graph carried out for three AA8015 specimen samples (7 mm thickness each) of the hot-rolled alloy is given in Figures 4-1, 4-2 and 4-3.

Figure 4-1: Stress-strain graph for the hot-rolled AA8015 specimen 7 mm thickness for sample 7_1

Figure 4-2: Stress-strain graph for the hot-rolled AA8015 specimen 7 mm thickness for sample 7_2
The hot working of AA8015 was done above the recrystallization temperature at 525 °C, as earlier mentioned. The results summarized in Table 4-1 were averagely computed for the three hot-rolled (HR) AA8015-alloy 7mm thickness specimen samples. It can be seen that hot-rolled AA8015-alloy 7 mm thickness specimen exhibited a yield strength of 67 MPa, which is the stress at which it begins to deform plastically. Likewise, it reveals a tensile strength of nearly 90 MPa, which is the maximum stress that it can support without fracturing, when stretched; and the material stiffness is found of approximately 19 GPa. These given stresses achieve an amount of plastic deformation in per cent elongation of just about 44%.

### 4.2.2 Mechanical tensile test measurements for reversing cold-rolled AA8015 specimen 1.2 mm thickness samples

The mechanical tensile test measurements result showing the stress-strain graph carried out for three reversing cold-rolled AA8015 specimen samples of 1.2 mm thickness each is given in Figures 4-4, 4-5 and 4-6.
Figure 4-4: Stress-strain graph for reversing cold-rolled AA8015 specimen 1.2 mm thickness for sample 1.2_1

Figure 4-5: Stress-strain graph for reversing cold-rolled AA8015 specimen 1.2 mm thickness for sample 1.2_2

Figure 4-6: Stress-strain graph for reversing cold-rolled AA8015 specimen 1.2 mm thickness for sample 1.2_3
Similarly, as mentioned earlier, the cold working of AA8015 was done below the recrystallization temperature at about 120 °C. Moreover, the cold-rolled AA8015 of 1.2 mm thickness was achieved in a reversing cold-rolling mill in which the work-piece (in this case HR AA8015 of 7 mm thickness) was passed forwards and backwards through a pair of work rolls. The results briefed in Table 4-2 disclose that the successively reduced cold-rolled AA8015 in four passes into a thickness of 1.2 mm unveiled yield strength (≈167 MPa), tensile strength (≈191 MPa) and material stiffness (≈71 GPa), respectively. Furthermore, the amount of ductility in per cent elongation gives approximately 8%.

4.2.3 Mechanical tensile test measurements for non-reversing cold-rolled AA8015 specimen 1 mm thickness samples

The mechanical tensile test measurements result showing the stress-strain graph carried out for three non-reversing cold-rolled AA8015 specimen samples of 1 mm thickness each is given in Figures 4-7, 4-8 and 4-9.

![Stress-strain graph for non-reversing cold-rolled AA8015 specimen 1 mm thickness for sample 1_1](image_url)

Figure 4-7: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 1 mm thickness for sample 1_1
Figure 4-8: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 1 mm thickness for sample 1_2

Figure 4-9: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 1 mm thickness for sample 1_3

Table 4-3: Summary of stress-strain graph results for non-reversing cold-rolled AA8015 specimen 1mm thickness for three samples

<table>
<thead>
<tr>
<th>Non-reversing cold rolled AA8015 1mm thickness specimen samples</th>
<th>0.2% offset Yield strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Amount of Ductility, % EI (l_f-l_o)/l_o</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1_1</td>
<td>210.00</td>
<td>232.85</td>
<td>55.55</td>
<td>9.10</td>
</tr>
<tr>
<td>Sample 1_2</td>
<td>182.50</td>
<td>223.52</td>
<td>72.26</td>
<td>9.10</td>
</tr>
<tr>
<td>Sample 1_3</td>
<td>192.50</td>
<td>229.55</td>
<td>67.11</td>
<td>9.50</td>
</tr>
<tr>
<td>Average</td>
<td>195.00</td>
<td>228.64</td>
<td>64.97</td>
<td>9.23</td>
</tr>
</tbody>
</table>
4.2.4 Mechanical tensile test measurements for non-reversing cold-rolled AA8015 specimen 2 mm thickness samples

The mechanical tensile test measurements result showing the stress-strain graph carried out for three non-reversing cold-rolled AA8015 specimen samples of 2 mm thickness each is given in Figures 4-10, 4-11 and 4-12.

**Figure 4-10:** Stress-strain graph for non-reversing cold-rolled AA8015 specimen 2 mm thickness for sample 2_1

**Figure 4-11:** Stress-strain graph for non-reversing cold-rolled AA8015 specimen 2 mm thickness for sample 2_2
Figure 4-12: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 2 mm thickness for sample 2_3

Table 4-4: Summary of stress-strain graph results for non-reversing cold-rolled AA8015 specimen 2 mm thickness for the three samples

<table>
<thead>
<tr>
<th>Non-reversing cold rolled AA8015 2mm thickness specimen samples</th>
<th>0.2% Offset Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Amount of Ductility, % El (l_f-l_o/l_o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 2_1</td>
<td>220.00</td>
<td>230.26</td>
<td>54.60</td>
<td>8.90</td>
</tr>
<tr>
<td>Sample 2_2</td>
<td>222.50</td>
<td>230.01</td>
<td>54.20</td>
<td>8.45</td>
</tr>
<tr>
<td>Sample 2_3</td>
<td>220.00</td>
<td>228.24</td>
<td>47.77</td>
<td>9.35</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>220.83</strong></td>
<td><strong>229.64</strong></td>
<td><strong>52.19</strong></td>
<td><strong>8.90</strong></td>
</tr>
</tbody>
</table>
4.2.5 Mechanical tensile test measurements for non-reversing cold-rolled AA8015 specimen 3 mm thickness samples

The mechanical tensile test measurements result showing the stress-strain graph carried out for three non-reversing cold-rolled AA8015 specimen samples of 3 mm thickness each is given in Figures 4-13, 4-14 and 4-15.

![Stress-strain graph for non-reversing cold-rolled AA8015 specimen 3 mm thickness for sample 3_1](image1)

Figure 4-13: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 3 mm thickness for sample 3_1

![Stress-strain graph for non-reversing cold-rolled AA8015 specimen 3 mm thickness for sample 3_2](image2)

Figure 4-14: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 3 mm thickness for sample 3_2
Figure 4-15: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 3 mm thickness for sample 3_3

Table 4-5: Summary of stress-strain graph results for non-reversing cold-rolled AA8015 specimen 3mm thickness for the three samples

<table>
<thead>
<tr>
<th>Non-reversing cold rolled AA8015 3mm thickness specimen samples</th>
<th>0.2% offset Yield strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Modulus of Elasticity (MPa)</th>
<th>Amount of Ductility, % El (l1-L0/l0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 3_1</td>
<td>196.00</td>
<td>208.04</td>
<td>40.53</td>
<td>10.00</td>
</tr>
<tr>
<td>Sample 3_2</td>
<td>194.00</td>
<td>197.10</td>
<td>31.23</td>
<td>9.50</td>
</tr>
<tr>
<td>Sample 3_3</td>
<td>192.50</td>
<td>197.43</td>
<td>34.06</td>
<td>9.65</td>
</tr>
<tr>
<td>Average</td>
<td>194.17</td>
<td>200.86</td>
<td>35.27</td>
<td>9.72</td>
</tr>
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</table>
4.2.6 Mechanical tensile test measurements for non-reversing cold-rolled AA8015 specimen 4 mm thickness samples

The mechanical tensile test measurements result showing the stress-strain graph carried out for three non-reversing cold-rolled AA8015 specimen samples of 4 mm thickness each is given in Figures 4-16, 4-17 and 4-18.

Figure 4-16: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 4 mm thickness for sample 4_1

Figure 4-17: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 4 mm thickness for sample 4_2
Figure 4-18: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 4 mm thickness for sample 4_3

Table 4-6: Summary of stress-strain graph results for non-reversing cold-rolled AA8015 specimen 4 mm thickness for the three samples

<table>
<thead>
<tr>
<th>Non-reversing cold rolled AA8015 4mm thickness specimen samples</th>
<th>0.2% offset Yield strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Amount of Ductility, % El (L_f - L_0/L_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 4_1</td>
<td>187.50</td>
<td>196.64</td>
<td>37.44</td>
<td>11.95</td>
</tr>
<tr>
<td>Sample 4_2</td>
<td>180.00</td>
<td>196.95</td>
<td>36.27</td>
<td>9.80</td>
</tr>
<tr>
<td>Sample 4_3</td>
<td>190.00</td>
<td>194.82</td>
<td>34.26</td>
<td>11.90</td>
</tr>
<tr>
<td>Average</td>
<td>185.83</td>
<td>196.14</td>
<td>35.99</td>
<td>11.22</td>
</tr>
</tbody>
</table>
4.2.7 Mechanical tensile test measurements for non-reversing cold-rolled AA8015 specimen 5 mm thickness samples

The mechanical tensile test measurements result showing the stress-strain graph carried out for three non-reversing cold-rolled AA8015 specimen samples of 5 mm thickness each is given in Figures 4-19, 4-20 and 4-21.

**Figure 4-19:** Stress-strain graph for non-reversing cold-rolled AA8015 specimen 5 mm thickness for sample 5_1

**Figure 4-20:** Stress-strain graph for non-reversing cold-rolled AA8015 specimen 5 mm thickness for sample 5_2
Figure 4-21: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 5 mm thickness for sample 5_3

Table 4-7: Summary of stress- strain graph results for non-reversing cold-rolled AA8015 specimen 5 mm thickness for the three samples

<table>
<thead>
<tr>
<th>Non-reversing cold rolled AA8015 5mm thickness specimen samples</th>
<th>0.2% offset yield strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Amount of Ductility, % El (l_f-l_0/l_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 5_1*</td>
<td>132.00</td>
<td>137.15</td>
<td>26.52</td>
<td>14.40</td>
</tr>
<tr>
<td>Sample 5_2</td>
<td>164.00</td>
<td>170.75</td>
<td>29.70</td>
<td>16.50</td>
</tr>
<tr>
<td>Sample 5_3</td>
<td>164.00</td>
<td>171.78</td>
<td>30.00</td>
<td>15.85</td>
</tr>
<tr>
<td>Average</td>
<td>164.00</td>
<td>171.27</td>
<td>29.85</td>
<td>16.18</td>
</tr>
</tbody>
</table>
4.2.8 Mechanical tensile test measurements for non-reversing cold-rolled AA8015 specimen 6 mm thickness samples

The mechanical tensile test measurements result showing the stress-strain graph carried out for three non-reversing cold-rolled AA8015 specimen samples of 6 mm thickness each is given in Figures 4-22, 4-23 and 4-24.

Figure 4-22: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 6mm thickness for sample 6_1

Figure 4-23: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 6 mm thickness for sample 6_2
Figure 4-24: Stress-strain graph for non-reversing cold-rolled AA8015 specimen 6 mm thickness for sample 6_3

Table 4-8: Summary of stress-strain graph results for non-reversing cold-rolled AA8015 specimen 6 mm thickness for the three samples

<table>
<thead>
<tr>
<th>Non-reversing cold rolled AA8015 thickness specimen samples</th>
<th>0.2% offset Yield strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Amount of Ductility, % El ((l_f/l_o))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 6_1</td>
<td>90.00</td>
<td>105.54</td>
<td>27.41</td>
<td>15.81</td>
</tr>
<tr>
<td>Sample 6_2</td>
<td>88.00</td>
<td>104.47</td>
<td>25.45</td>
<td>15.80</td>
</tr>
<tr>
<td>Sample 6_3*</td>
<td>118.00</td>
<td>130.69</td>
<td>28.11</td>
<td>16.15</td>
</tr>
<tr>
<td>Average</td>
<td>89.00</td>
<td>105.01</td>
<td>26.43</td>
<td>15.81</td>
</tr>
</tbody>
</table>

It should be noted that all the data from the tensile test specimen samples indicated a linear behaviour. However, specimen samples 5_1 and 6_3 were discarded; because the material properties (yield strength and tensile strength) values showed a lower and a higher amount of deviation respectively than the others in the set.

Figure 4-7 to Figure 4-24 show the stress-strain relationship graphs for non-reversible cold-rolled AA8015 specimen samples of thickness variations ranging from 1 mm to 6 mm at intervals of 1 mm. The material properties of each cold-rolled thickness variation are recorded in Tables 4-3, 4-4, 4-5, 4-6, 4-7, and 4-8. Table 4-9 shows the micro-hardness values for the hot-rolled, reversing cold-rolled and non-reversing cold-rolled AA8015 specimen samples. Subsequently, Figure 4-25 reveals the disparity of the Hardness Values (HV) between these specimen samples with clarity by using a column chart. Furthermore, Figure 4-26 makes known the material properties of the eight AA8015 tensile specimen samples by using a clustered column chart.
Meanwhile, in non-reversing cold-rolling mills, the work rolls revolve continuously in the same direction; and they require re-feeding (re-passing) of the material again through the mills.

The Vickers Micro-hardness values (HV) of the cold-rolled AA8015 samples clearly show a trending increase compared to the hot-rolled samples with 7 mm thickness, see Table 4-9 and Figure 4-25. The findings from the HV influence on reversing and non-reversing cold-rolled AA8015 specimen samples show that for reversing cold-rolled samples with 83 % successive cold work, the hardness increases with about 54% when compared to the hot-rolled sample of 7 mm thickness. Likewise, for the non-reversing cold-rolled samples, the six samples reduced at each pass schedule with 14.2% cold work shows an increasing trend in hardness values; as the gauge thickness is reduced. However, a slight reduction in hardness value is experienced with a gauge thickness of 1mm. This shows that the hardness value of cold-rolled AA8015 alloy increases with the per cent cold work; but it starts to decrease when the gauge thickness is ≤ 1 mm.
Table 4-9: Micro-hardness measurements for rolled specimen samples

<table>
<thead>
<tr>
<th>AA8015 specimen samples</th>
<th>Hot rolled (7mm thickness)</th>
<th>Reversing Cold rolled (1.2mm thickness)</th>
<th>Non-reversing Cold rolled (6mm thickness)</th>
<th>Non-reversing Cold rolled (5mm thickness)</th>
<th>Non-reversing Cold rolled (4mm thickness)</th>
<th>Non-reversing Cold rolled (3mm thickness)</th>
<th>Non-reversing Cold rolled (2mm thickness)</th>
<th>Non-reversing Cold rolled (1mm thickness)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vickers Micro-hardness Values (HV)</td>
<td>39</td>
<td>60</td>
<td>48</td>
<td>52</td>
<td>66</td>
<td>69</td>
<td>73</td>
<td>67</td>
</tr>
</tbody>
</table>

Figure 4-25: Column chart showing the influence of cold work on the Hardness Values (HV) of reversing and non-reversing cold-rolled AA8015 specimen samples

Note:
HR denotes hot rolled; R_CR denotes reversing cold-rolled, and NR_CR denotes non-reversing cold-rolled.

The stress-strain behaviour of the rolled AA8015-alloy samples is remarkable. The yield strength, tensile strength, elastic modulus and the amount of ductility can be deduced from the stress-strain behaviour of the hot-rolled, reversing cold-rolled and non-reversing cold-rolled AA8015-alloy samples; and this is given in Figure 4-26. The material properties of the cold-rolled samples clearly shows the effect of strain hardening in cold working. The reversing cold-rolled AA8015-alloy sample exhibits yield strength, tensile strength and elastic modulus equivalent to almost three-times, two-times and nearly four-times that of the hot-rolled sample with the amount of ductility reduced to 8%.

In addition, the non-reversing cold-rolled samples exhibit increasing values of strength and elastic modulus in all the six pass schedules, with decreasing amounts of ductility. However, the strength increases with the percentage of cold work except for the 1 mm gauge thickness that shows decreased yield strength, nearly equal tensile strength and ductility with the previous cold-worked thickness of 2 mm. Likewise, the amount of ductility reduces with the percent cold work.
Microstructural analysis of rolled AA8015 specimen samples

The microstructure of a metallic material simply describes the appearance of the material’s surface morphology on a nm-cm length scale in which the arrangement of the phases and defects within the material are revealed [192-194]. In order to get a deeper understanding of the behaviour of the different rolled AA8015 alloy and the evolving properties; as it is successively cold-rolled into a thinner gauge thickness, a microstructural evaluation was performed on the eight processed AA8015 specimen samples identified – by using a light optical microscope and scanning-electron microscopy (SEM).

Microstructural analysis was done on both the longitudinal and transverse sections in the rolling direction of the hot-rolled, reversing cold-rolled and non-reversing cold-rolled AA8015 specimen samples. The entire rolled AA8015 specimen samples for microstructural evaluation were all mounted, grinded, polished and etched on both the longitudinal and in the transverse sections in the rolling direction. The grain sizes revealed in the micrographs were measured and recorded.

4.3.1 Microstructural observation of hot-rolled AA8015 sample

Figures 4-27 and 4-28 show the optical and SEM micrographs grain structure of hot-rolled AA8015-alloy both in the longitudinal and the transverse section. The optical micrograph grain size measurement reveals an average grain size of 3.426 µm and 2.406 µm for the longitudinal and transverse section, respectively. Densely populated smaller grains are revealed in the transverse section when compared to the longitudinal section. This is also confirmed in the SEM images; showing that the density of grain boundaries observed is smaller in the longitudinal section, thus encouraging dislocation movement.
4.3.2 Microstructural observation of reversing cold-rolled AA8015 sample

The microstructure of reversing cold-rolled AA8015 sample reduced to 1.2 mm thickness is revealed in Figures 4-29 and 4-30. Average grain size measurements give 7.914 µm and 3.178 µm for the longitudinal and transverse sections, respectively in the optical micrographs. The grain size in the longitudinal section is rather larger, as expected; due to the strain-hardening effect on the rolling surface than for the examined hot-rolled samples given in Section 4.3.1. Accordingly, approximately twice the grain size of the hot-rolled grains is found in the longitudinal section of the reversing cold-rolled grains. Likewise, in the transverse section, densely populated grains are observed; and these are relatively larger than the hot rolled grains.
However, the grains are seen to be more compressed than those of the hot-rolled grains, bringing about stronger bonding, which explains the higher strength observed in Figure 4-26 on page ninety-one.

Figure 4-29: Light optical micrographs of reversing cold-rolled AA8015 sample at 500x magnification: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy

Figure 4-30: SEM images of reversing cold-rolled AA8015 sample showing magnified grain structures: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy
4.3.3 Microstructural observation of non-reversing cold-rolled AA8015 samples

The evolving microstructure of non-reversing cold-rolled AA8015-alloy samples comprising six different cold-rolled thickness gauges are shown below. The amount of cold work done on each thickness gauge reduction is approximately 14.3%.

Figure 4-31: Light optical micrographs of non-reversing cold-rolled AA8015 sample (6 mm thickness) at 500-x magnification: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy

Figure 4-32: SEM images of non-reversing cold-rolled AA8015 sample (6 mm thickness) showing magnified grain structures: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy
The light optical micrographs and SEM images for a non-reversing cold-rolled AA8015-alloy 6 mm thickness in gauge is revealed in Figures 4-31 and 4-32, respectively. The average grain sizes of 4.826 µm and 3.96 µm were recorded depicting larger grain size compared to the hot-rolled sample in Section 4.3.1.

Figure 4-33: Light optical micrographs of non-reversing cold-rolled AA8015 sample (5 mm thickness) at 500x magnification: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy

Figure 4-34: SEM images of non-reversing cold-rolled AA8015 sample (5 mm thickness) showing magnified grain structures: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy
Figure 4-35: Light optical micrographs of non-reversing cold-rolled AA8015 sample (4 mm thickness) at 500x magnification: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy

Figure 4-36: SEM images of non-reversing cold-rolled AA8015 sample (4 mm thickness) showing magnified grain structures: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy
Figure 4-37: Light optical micrographs of non-reversing cold-rolled AA8015 sample (3 mm thickness) at 500x magnification: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy

Figure 4-38: SEM images of non-reversing cold-rolled AA8015 sample (3 mm thickness) showing magnified grain structures: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy
Figure 4-39: Light optical micrographs of non-reversing cold-rolled AA8015 sample (2 mm thickness) at 500x magnification: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy

Figure 4-40: SEM images of non-reversing cold-rolled AA8015 sample (2 mm thickness) showing magnified grain structures: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy
Figures 4-33 to 4-42 depict the microstructural micrographs and SEM images of non-reversing cold-rolled AA8015-alloy of varying thickness gauge of cold working in 5 mm, 4 mm, 3 mm, 2 mm and 1 mm thickness. Average grain sizes of 4.043 µm, 2.368 µm, 2.128 µm, 1.442 µm and 5.399 µm were measured in the longitudinal section for the non-reversing cold-worked thickness gauges, respectively. A reduction in the grain size was observed; as 14.3% cold work is achieved on each gauge thickness, except for an
observed increment in grain size of 1 mm thickness in the cold-worked sample. Further measurement in the transverse section reveals average grain sizes of 3.391 µm, 2.29 µm, 2.005 µm, 1.366 µm and 4.68 µm for cold-rolled thickness gauges varying from 5 mm to 1 mm. This also confirms the same trend in the reduction of grain size from 5 mm to 2 mm thickness; and sharp rise in 1 mm thickness in the horizontal section.

However, the evolving microstructural observations of the non-reversing cold-rolled AA8015-alloy of different reduced thickness gauge have different trends in grain size when compared with the hot-rolled and reversing cold-rolled grain structures. This can be linked to the abrupt method of the non-reversing cold-rolling process.

Moreover, the hot-rolled, reversing cold-rolled and non-reversing cold-rolled AA8015-alloy all show equiaxed grain structures and compact, lesser grain sizes in the transverse section, depicting the effect of strain hardening.

In addition, the SEM images of the entire eight AA8015-alloy samples show bright particles. In order to analyse the compositional differences in the microstructure and to identify these particles, energy dispersive x-rays and mapping were carried out at selected areas, as shown in Figure 4-43.
Figure 4-43: (a) SEM image showing bright particles of AA8015-alloy. (b-g) EDS spectra showing the elemental composition of the selected precipitates (1-6), respectively.
It can be observed that Manganese (Mn) atoms seem to be heterogeneously present in solid solution in the aluminium matrix. Mn atoms dissolve in the aluminium matrix, resulting in a supersaturated solid solution, which decomposes via the precipitation of the dispersed particles during the homogenization prior to the hot rolling [142].

The mapping shown in Figure 4-44 illustrates the distribution of aluminium in both the hot-rolled and in the cold-rolled AA8015-alloy samples. The mapping results are not quantitative; therefore, the colour difference between the maps is not comparable to determine the differences in composition.

The map images demonstrate that the distribution of aluminium is homogeneous for both the hot-rolled and the cold rolled samples.

![EDS elemental mapping of (a) hot-rolled AA8015-alloy (b) cold-rolled AA8015-alloy](image)

**Figure 4-44: EDS elemental mapping of (a) hot-rolled AA8015-alloy (b) cold-rolled AA8015-alloy**
4.4 Corrosion behaviour of hot-rolled and cold-rolled AA8015 alloy in natural sea water

This section presents the findings and a discussion of the electrochemical corrosion of mechanically processed hot-rolled and cold-rolled AA8015-alloy in varying degrees of surface roughness in natural sea water solution. The natural sea water with a pH of 7.04 was taken from the sea at Durban. Table 4-10 depicts the chemical composition of the sea water at 3.5 % salinity. The major ion in parts per million (ppm) is shown. Also, Table 4-11 shows the roughness values of corrosion samples measured under various surface conditions.

Table 4-10: Major ion composition of sea water at 3.5% salinity [195]

<table>
<thead>
<tr>
<th>Element</th>
<th>PPM in sea water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride (Cl⁻)</td>
<td>18980</td>
</tr>
<tr>
<td>Sodium (Na⁺)</td>
<td>10556</td>
</tr>
<tr>
<td>Sulphate (SO₄²⁻)</td>
<td>2649</td>
</tr>
<tr>
<td>Magnesium (Mg²⁺)</td>
<td>1262</td>
</tr>
<tr>
<td>Calcium (Ca²⁺)</td>
<td>400</td>
</tr>
<tr>
<td>Potassium (K⁺)</td>
<td>380</td>
</tr>
<tr>
<td>Bicarbonates (HCO₃⁻)</td>
<td>140</td>
</tr>
<tr>
<td>Strontium (Sr²⁺)</td>
<td>13</td>
</tr>
<tr>
<td>Bromide (Br⁻)</td>
<td>65</td>
</tr>
<tr>
<td>Borate (BO₃³⁻)</td>
<td>26</td>
</tr>
<tr>
<td>Fluoride (F⁻)</td>
<td>1</td>
</tr>
<tr>
<td>Silicate (SiO₃²⁻)</td>
<td>1</td>
</tr>
<tr>
<td>Others</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4-11: Surface roughness ($R_a$) values of corrosion samples under various surface conditions

<table>
<thead>
<tr>
<th>AA8015 alloy</th>
<th>Surface roughness value with 320 grit SiC paper ($R_a$)</th>
<th>Surface roughness value with 800 grit SiC paper ($R_a$)</th>
<th>Surface roughness value with 1200 grit SiC paper ($R_a$)</th>
<th>Surface roughness value with diamond polishing ($R_a$)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-rolled</td>
<td>1.37</td>
<td>0.65</td>
<td>0.19</td>
<td>0.10</td>
<td>µm</td>
</tr>
<tr>
<td>samples</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold-rolled</td>
<td>1.54</td>
<td>0.83</td>
<td>0.18</td>
<td>0.04</td>
<td>µm</td>
</tr>
<tr>
<td>samples</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.4.1 Open circuit potential ($E_{oc}$) measurements

As earlier mentioned, an open glass cell was used for the electrochemical measurements. The polarization cell set up consisted of rolled AA8015 samples with a working electrode immersed in natural sea water, along with a Silver/Silver Chloride reference electrode. The potential of the working electrodes was measured under open circuit conditions at room temperature, as a function of time until a steady state was achieved. A duration of an hour in all cases was found to be suitable for this purpose. The variation of the $E_{oc}$ with time obtained in natural sea water is shown in Figures 4-45 to 4-52. The steady-state $E_{oc}$ for each hot-rolled and cold-rolled AA8015-alloy in sea water at four varying surface roughness was taken at the last 3600 seconds of measurement and recorded in Tables 4-12 and 4-13. Each of the four different surface roughness values was confirmed with three samples for repeatability and precision.

Figure 4-45: Variation of open circuit potential with time for hot-rolled AA8015-alloy (Ra≈1.37 µm) immersed in natural sea water

Figure 4-46: Variation of open circuit potential with time for hot-rolled AA8015-alloy (Ra≈0.65) immersed in natural sea water
Figure 4-47: Variation of open circuit potential with time for hot-rolled AA8015-alloy (Ra≈0.19) immersed in natural sea water.

Figure 4-48: Variation of open circuit potential with time for hot-rolled AA8015-alloy (Ra≈0.10) immersed in natural sea water.
Figure 4-49: Variation of open circuit potential with time for cold-rolled AA8015-alloy (Ra≈1.54) immersed in natural sea water.

Figure 4-50: Variation of open circuit potential with time for cold-rolled AA8015-alloy (Ra≈0.83) immersed in natural sea water.
The variations of the open circuit potential with the time plot for all the rolled AA8015 samples show a steady state variation almost throughout the time duration. Hot-rolled and cold-rolled AA8015 samples with surface roughness values below 0.20 µm were observed to have relatively stable drifting within 0.03 V. The list of the steady-state open-circuit potential, $E_{oc}$, values obtained in each hot-rolled and cold-rolled AA8015 samples for the four different surface roughness values, all show electronegative potentials; and these are given in Tables 4-12 and 4-13 respectively. Significant observation observes that the $E_{oc}$ values of the cold-rolled samples are more negative than the hot-rolled samples. This indicates that the cold-rolled AA8015-alloy has a greater tendency to oxidize. This may not only be due to the changes in the
microstructure, as a result of the alloying element, but also to the strain hardening effect on the cold-rolled alloy. Furthermore, it is possible to predict from the results that both hot-rolled and cold-rolled metal alloys would not have any significant effect when they are both in contact with each other in natural sea water solution. The reason is that bimetallic corrosion only occurs when the difference in the potential is at least 0.1 V [196].

Table 4-12: Open circuit potential ($E_{oc}$) for hot-rolled AA8015 samples against Ag/AgCl with varying degrees of surface roughness

<table>
<thead>
<tr>
<th>AA8015 alloy samples</th>
<th>Surface roughness Ra≈1.37µm</th>
<th>Surface roughness Ra≈0.65µm</th>
<th>Surface roughness Ra≈0.19µm</th>
<th>Surface roughness Ra≈0.10µm</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>-0.693</td>
<td>-0.702</td>
<td>-0.706</td>
<td>-0.714</td>
<td>V</td>
</tr>
<tr>
<td>Sample 2</td>
<td>-0.696</td>
<td>-0.720</td>
<td>-0.699</td>
<td>-0.722</td>
<td>V</td>
</tr>
<tr>
<td>Sample 3</td>
<td>-0.714</td>
<td>-0.714</td>
<td>-0.688</td>
<td>-0.718</td>
<td>V</td>
</tr>
</tbody>
</table>

Table 4-13: Open circuit potential ($E_{oc}$) for cold-rolled AA8015 samples against Ag/AgCl with varying degrees of surface roughness

<table>
<thead>
<tr>
<th>AA8015 alloy samples</th>
<th>Surface roughness Ra≈1.54µm</th>
<th>Surface roughness Ra≈0.83µm</th>
<th>Surface roughness Ra≈0.18µm</th>
<th>Surface roughness Ra≈0.04µm</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>-0.739</td>
<td>-0.740</td>
<td>-0.713</td>
<td>-0.734</td>
<td>V</td>
</tr>
<tr>
<td>Sample 2</td>
<td>-0.714</td>
<td>-0.728</td>
<td>-0.723</td>
<td>-0.710</td>
<td>V</td>
</tr>
<tr>
<td>Sample 3</td>
<td>-0.740</td>
<td>-0.759</td>
<td>-0.703</td>
<td>-0.714</td>
<td>V</td>
</tr>
</tbody>
</table>

4.4.2 Polarization curve measurements

The polarization curves were determined, based on a conventional three-electrode glass cell, as earlier explained. This glass cell consists of AA8015 sample working electrode, Ag/AgCl reference electrode, and a platinum wire electrode immersed in natural sea water solution. Electrochemical corrosion experiments were carried out; and the current response was measured over a potential range from -250 mV to +250 mV, with respect to the open circuit potential at a scan rate of 0.167 mV/s. At least three scans were conducted for each surface roughness condition to confirm the precision of the results. Figures 4-53 and 4-54 show the polarization curve for the hot-rolled and the cold-rolled AA8015 samples for each four surface roughness conditions.
Figure 4-53: Polarization curves of hot-rolled AA8015-alloy immersed in natural sea water at (a) $Ra \approx 1.37 \, \mu m$; (b) $Ra \approx 0.65 \, \mu m$; (c) $Ra \approx 0.19 \, \mu m$; (d) $Ra \approx 0.19 \, \mu m$
Observation of the entire shape of the polarization curves obtained from both the hot-rolled and the cold-rolled AA8015 samples for the four different surface conditions show asymmetric curves. The polarization curves show Tafel behaviour on the cathodic side extended over a wider potential range than that on the anodic side. In addition, the anodic current rose more steeply with changes in potential than the cathodic current. However, significant observation reveals electrochemical noise in almost all the polarization curves, which is because of the noisy electrode response. This occurrence suggests evidence of pitting corrosion.

4.4.3 Corrosion rate analysis

The Slope and Tafel analyses are presented on the hot-rolled and on the cold-rolled AA8015 samples at each surface-roughness condition.
In the Slope analysis, the current-potential data obtained were fitted to obtain the slopes by potential range markers. These are anodic and cathodic potentials ($E_a$ & $E_c$) at points on the anodic and cathodic curve, respectively.

Consequently, the Tafel analysis of the polarization curves involves plotting the obtained data as logarithms of current against potential for both the anodic and cathodic branches. Straight lines that best fit the data at high potentials were achieved at selected potential range markers on both anodic and cathodic curves. Extrapolating of the straight lines was done until they intersected. This point of intersection yields the corrosion current density $I_{corr}$ and the corrosion potential $E_{corr}$. Figures 4-55 and 4-56 show the slope and Tafel analysis for the hot-rolled AA8015 sample one (1) at a surface roughness of $Ra \approx 1.37 \, \mu m$. The slope and Tafel analysis for the other ones are given in Appendix B.

**Figure 4-55: Slope analysis of hot-rolled AA8015 (Sample 1 for $Ra \approx 1.37 \, \mu m$) $E_{a1} = -0.720 \, V$; $E_{c2} = -0.704 \, V$**

**Figure 4-56: Tafel analysis of hot-rolled AA8015 (Sample 1 for $Ra \approx 1.37 \, \mu m$) $E_{a1} = -0.827 \, V$; $E_{a2} = -0.801 \, V$; $E_{c1} = -0.657 \, V$; $E_{c2} = -0.645 \, V$**
The corresponding $E_{corr}$ in volts, $I_{corr}$ in ampere, polarization resistance ($R_p$) in ohm and corrosion rate in millimetres per year were calculated from the slopes; and they are given in Tables 4-14 to 4-21.

Prior to the calculation, the following parameters were defined as constants for the AA8015-alloy samples:

- **Surface area** = 1.0 cm$^2$
- **Equivalent weight** = 8.97 g
- **Density** = 2.7 g/cm$^3$

For slope analysis

- **Anodic slope of Tafel plot, $B_a$** = 0.1 V/dec
- **Cathodic slope of Tafel plot, $B_c$** = 0.1 V/dec

### Table 4-14: Corrosion rate analysis of hot-rolled AA8015-alloy at Ra≈1.37 µm

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{corr}$ (V)</td>
<td>Slope data</td>
<td>Tafel data</td>
</tr>
<tr>
<td>$I_{corr}$ (A)</td>
<td>-0.7018</td>
<td>-0.7281</td>
</tr>
<tr>
<td>$I_{corr}$ (A/cm$^2$)</td>
<td>7.70E-07</td>
<td>1.12E-06</td>
</tr>
<tr>
<td>$R_p$ (Ohm)</td>
<td>2.82E+04</td>
<td>9879</td>
</tr>
<tr>
<td>$B_a$ (V/dec)</td>
<td>0.1</td>
<td>0.027</td>
</tr>
<tr>
<td>$B_c$ (V/dec)</td>
<td>0.1</td>
<td>0.618</td>
</tr>
<tr>
<td>C. Rate (mm/y)</td>
<td>0.008374</td>
<td>0.01217</td>
</tr>
</tbody>
</table>

### Table 4-15: Corrosion rate analysis of hot-rolled AA8015-alloy at Ra≈0.65 µm

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{corr}$ (V)</td>
<td>Slope data</td>
<td>Tafel data</td>
</tr>
<tr>
<td>$I_{corr}$ (A)</td>
<td>-0.6979</td>
<td>-0.7625</td>
</tr>
<tr>
<td>$I_{corr}$ (A/cm$^2$)</td>
<td>3.57E-07</td>
<td>9.64E-07</td>
</tr>
<tr>
<td>$R_p$ (Ohm)</td>
<td>3.57E-07</td>
<td>9.64E-07</td>
</tr>
<tr>
<td>$B_a$ (V/dec)</td>
<td>0.1</td>
<td>0.033</td>
</tr>
<tr>
<td>$B_c$ (V/dec)</td>
<td>0.1</td>
<td>0.718</td>
</tr>
<tr>
<td>C. Rate (mm/y)</td>
<td>0.003882</td>
<td>0.01048</td>
</tr>
</tbody>
</table>
### Table 4-16: Corrosion rate analysis of hot-rolled AA8015-alloy at Ra≈0.19 µm

<table>
<thead>
<tr>
<th></th>
<th>Sample 1</th>
<th></th>
<th>Sample 2</th>
<th></th>
<th>Sample 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slope data</strong></td>
<td><strong>Tafel data</strong></td>
<td><strong>Slope data</strong></td>
<td><strong>Tafel data</strong></td>
<td><strong>Slope data</strong></td>
<td><strong>Tafel data</strong></td>
<td><strong>Slope data</strong></td>
</tr>
<tr>
<td>$E_{corr}$ (V)</td>
<td>-0.7002</td>
<td>-0.716</td>
<td>-0.6801</td>
<td>-0.6962</td>
<td>-0.6867</td>
<td>-0.7104</td>
</tr>
<tr>
<td>$I_{corr}$ (A)</td>
<td>2.60E-07</td>
<td>8.26E-07</td>
<td>3.58E-06</td>
<td>2.77E-06</td>
<td>4.25E-07</td>
<td>1.21E-06</td>
</tr>
<tr>
<td>$I_{corr}$ (A/cm$^2$)</td>
<td>2.60E-07</td>
<td>8.26E-07</td>
<td>3.58E-06</td>
<td>2.77E-06</td>
<td>4.25E-07</td>
<td>1.21E-06</td>
</tr>
<tr>
<td>$R_p$ (Ohm)</td>
<td>8.34E+04</td>
<td>1.95E+04</td>
<td>6064</td>
<td>5308</td>
<td>5.11E+04</td>
<td>1.24E+04</td>
</tr>
<tr>
<td>$B_a$ (V/dec)</td>
<td>0.1</td>
<td>0.04</td>
<td>0.1</td>
<td>0.036</td>
<td>0.1</td>
<td>0.037</td>
</tr>
<tr>
<td>$B_c$ (V/dec)</td>
<td>0.1</td>
<td>0.465</td>
<td>0.1</td>
<td>0.544</td>
<td>0.1</td>
<td>0.468</td>
</tr>
<tr>
<td>C. Rate (mm/y)</td>
<td>0.00283</td>
<td>0.008982</td>
<td>0.03892</td>
<td>0.03006</td>
<td>0.004617</td>
<td>0.131</td>
</tr>
</tbody>
</table>

### Table 4-17: Corrosion rate analysis of hot-rolled AA8015-alloy at Ra≈0.10 µm

<table>
<thead>
<tr>
<th></th>
<th>Sample 1</th>
<th></th>
<th>Sample 2</th>
<th></th>
<th>Sample 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slope data</strong></td>
<td><strong>Tafel data</strong></td>
<td><strong>Slope data</strong></td>
<td><strong>Tafel data</strong></td>
<td><strong>Slope data</strong></td>
<td><strong>Tafel data</strong></td>
<td><strong>Slope data</strong></td>
</tr>
<tr>
<td>$E_{corr}$ (V)</td>
<td>-0.6946</td>
<td>-0.7289</td>
<td>-0.7178</td>
<td>-0.754</td>
<td>-0.7221</td>
<td>-0.7245</td>
</tr>
<tr>
<td>$I_{corr}$ (A)</td>
<td>1.55E-07</td>
<td>6.22E-07</td>
<td>1.63E-07</td>
<td>6.47E-07</td>
<td>1.12E-07</td>
<td>9.16E-07</td>
</tr>
<tr>
<td>$I_{corr}$ (A/cm$^2$)</td>
<td>1.55E-07</td>
<td>6.22E-07</td>
<td>1.63E-07</td>
<td>6.47E-07</td>
<td>1.12E-07</td>
<td>9.16E-07</td>
</tr>
<tr>
<td>$R_p$ (Ohm)</td>
<td>1.41E+05</td>
<td>2.51E+04*</td>
<td>1.33E+05</td>
<td>3.26E+04*</td>
<td>1.93E+05</td>
<td>2.07E+04</td>
</tr>
<tr>
<td>$B_a$ (V/dec)</td>
<td>0.1</td>
<td>0.04</td>
<td>0.1</td>
<td>0.055</td>
<td>0.1</td>
<td>0.043</td>
</tr>
<tr>
<td>$B_c$ (V/dec)</td>
<td>0.1</td>
<td>0.365</td>
<td>0.1</td>
<td>0.398</td>
<td>0.1</td>
<td>0.514</td>
</tr>
<tr>
<td>C. Rate (mm/y)</td>
<td>0.00168</td>
<td>0.006758*</td>
<td>0.001774</td>
<td>0.007029*</td>
<td>0.001221</td>
<td>0.009957</td>
</tr>
</tbody>
</table>

### Table 4-18: Corrosion rate analysis of cold-rolled AA8015-alloy at Ra≈1.54 µm

<table>
<thead>
<tr>
<th></th>
<th>Sample 1</th>
<th></th>
<th>Sample 2</th>
<th></th>
<th>Sample 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slope data</strong></td>
<td><strong>Tafel data</strong></td>
<td><strong>Slope data</strong></td>
<td><strong>Tafel data</strong></td>
<td><strong>Slope data</strong></td>
<td><strong>Tafel data</strong></td>
<td><strong>Slope data</strong></td>
</tr>
<tr>
<td>$E_{corr}$ (V)</td>
<td>-0.7344</td>
<td>-0.7746</td>
<td>-0.7228</td>
<td>-0.7289</td>
<td>-0.7297</td>
<td>-0.7324</td>
</tr>
<tr>
<td>$I_{corr}$ (A)</td>
<td>3.07E-07</td>
<td>9.78E-07</td>
<td>1.89E-06</td>
<td>1.42E-06</td>
<td>1.46E-06</td>
<td>1.16E-06</td>
</tr>
<tr>
<td>$I_{corr}$ (A/cm$^2$)</td>
<td>3.07E-07</td>
<td>9.78E-07</td>
<td>1.89E-06</td>
<td>1.42E-06</td>
<td>1.46E-06</td>
<td>1.16E-06</td>
</tr>
<tr>
<td>$R_p$ (Ohm)</td>
<td>7.08E+04</td>
<td>1.40E+04</td>
<td>1.15E+04</td>
<td>6051</td>
<td>1.49E+04</td>
<td>7173</td>
</tr>
<tr>
<td>$B_a$ (V/dec)</td>
<td>0.1</td>
<td>0.036</td>
<td>0.1</td>
<td>0.021</td>
<td>0.1</td>
<td>0.02</td>
</tr>
<tr>
<td>$B_c$ (V/dec)</td>
<td>0.1</td>
<td>0.266</td>
<td>0.1</td>
<td>0.288</td>
<td>0.1</td>
<td>0.485</td>
</tr>
<tr>
<td>C. Rate (mm/y)</td>
<td>0.003335</td>
<td>0.01063</td>
<td>0.0205</td>
<td>0.01538</td>
<td>0.01582</td>
<td>0.01266</td>
</tr>
</tbody>
</table>
Table 4-19: Corrosion rate analysis of cold-rolled AA8015-alloy at Ra≈0.83 µm

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Slope data</strong></td>
<td><strong>Tafel data</strong></td>
<td><strong>Slope data</strong></td>
</tr>
<tr>
<td><strong>E&lt;sub&gt;corr&lt;/sub&gt; (V)</strong></td>
<td>-0.735</td>
<td>-0.735</td>
</tr>
<tr>
<td><strong>I&lt;sub&gt;corr&lt;/sub&gt; (A)</strong></td>
<td>8.26E-07</td>
<td>1.17E-06</td>
</tr>
<tr>
<td><strong>I&lt;sub&gt;corr&lt;/sub&gt; (A/cm&lt;sup&gt;2&lt;/sup&gt;)</strong></td>
<td>8.26E-07</td>
<td>1.17E-06</td>
</tr>
<tr>
<td><strong>R&lt;sub&gt;p&lt;/sub&gt; (Ohm)</strong></td>
<td>2.63E+04</td>
<td>8021*</td>
</tr>
<tr>
<td><strong>B&lt;sub&gt;a&lt;/sub&gt; (V/dec)</strong></td>
<td>0.1</td>
<td>0.022</td>
</tr>
<tr>
<td><strong>B&lt;sub&gt;c&lt;/sub&gt; (V/dec)</strong></td>
<td>0.1</td>
<td>0.813</td>
</tr>
<tr>
<td><strong>C. Rate (mm/y)</strong></td>
<td>0.008982</td>
<td>0.01268</td>
</tr>
</tbody>
</table>

Table 4-20: Corrosion rate analysis of cold-rolled AA8015-alloy at Ra≈0.18 µm

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Slope data</strong></td>
<td><strong>Tafel data</strong></td>
<td><strong>Slope data</strong></td>
</tr>
<tr>
<td><strong>E&lt;sub&gt;corr&lt;/sub&gt; (V)</strong></td>
<td>-0.6813</td>
<td>-0.7509</td>
</tr>
<tr>
<td><strong>I&lt;sub&gt;corr&lt;/sub&gt; (A)</strong></td>
<td>4.97E-06</td>
<td>2.53E-06</td>
</tr>
<tr>
<td><strong>I&lt;sub&gt;corr&lt;/sub&gt; (A/cm&lt;sup&gt;2&lt;/sup&gt;)</strong></td>
<td>4.97E-06</td>
<td>2.53E-06</td>
</tr>
<tr>
<td><strong>R&lt;sub&gt;p&lt;/sub&gt; (Ohm)</strong></td>
<td>4368</td>
<td>8236</td>
</tr>
<tr>
<td><strong>B&lt;sub&gt;a&lt;/sub&gt; (V/dec)</strong></td>
<td>0.1</td>
<td>0.054</td>
</tr>
<tr>
<td><strong>B&lt;sub&gt;c&lt;/sub&gt; (V/dec)</strong></td>
<td>0.1</td>
<td>0.458</td>
</tr>
<tr>
<td><strong>C. Rate (mm/y)</strong></td>
<td>0.05403</td>
<td>0.02749</td>
</tr>
</tbody>
</table>

Table 4-21: Corrosion rate analysis of cold-rolled AA8015-alloy at Ra≈0.04 µm

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Slope data</strong></td>
<td><strong>Tafel data</strong></td>
<td><strong>Slope data</strong></td>
</tr>
<tr>
<td><strong>E&lt;sub&gt;corr&lt;/sub&gt; (V)</strong></td>
<td>-0.6695</td>
<td>-0.683</td>
</tr>
<tr>
<td><strong>I&lt;sub&gt;corr&lt;/sub&gt; (A)</strong></td>
<td>6.26E-06</td>
<td>3.89E-06</td>
</tr>
<tr>
<td><strong>I&lt;sub&gt;corr&lt;/sub&gt; (A/cm&lt;sup&gt;2&lt;/sup&gt;)</strong></td>
<td>6.26E-06</td>
<td>3.89E-06</td>
</tr>
<tr>
<td><strong>R&lt;sub&gt;p&lt;/sub&gt; (Ohm)</strong></td>
<td>3469</td>
<td>4089</td>
</tr>
<tr>
<td><strong>B&lt;sub&gt;a&lt;/sub&gt; (V/dec)</strong></td>
<td>0.1</td>
<td>0.039</td>
</tr>
<tr>
<td><strong>B&lt;sub&gt;c&lt;/sub&gt; (V/dec)</strong></td>
<td>0.1</td>
<td>0.721</td>
</tr>
<tr>
<td><strong>C. Rate (mm/y)</strong></td>
<td>0.06805</td>
<td>0.04223</td>
</tr>
</tbody>
</table>

It is important to note that the polarization resistance and the corrosion rate computed for three (3) samples at different surface roughness values of both the hot- and the cold-rolled AA8015-alloy given in Tables 4-14 to 4-21 for the slope analysis are not considered for discussion; but they serve as a reference in
extrapolating the straight lines to determine the point of intersection. The reason is due to the constants defined for the anodic and the cathodic slopes ($B_a$ and $B_c$ respectively).

In the Tafel analysis, a wide range of averaged $R_p$ values from 4.244 kΩ to 28.860 kΩ and 9.088 kΩ to 21.923 kΩ for the hot- and cold-rolled AA8015 samples respectively, at the different surface roughness values recorded were obtained. See Tables 4-22 and 4-23. A significant observation reveals an increase in $R_p$ values as the AA8015-alloy surface roughness, $R_a$, decreases (or gets smoother) for both the hot- and the cold-rolled AA8015-alloys.

The hot-rolled AA8015 surface with a roughness of $R_a \approx 1.37$ µm shows the lowest $R_p$ value (4.244 kΩ). This postulate a very strong attack or dissolution of the aluminium alloy. While the $R_p$ value (28.860 kΩ) of the hot-rolled AA8015-alloy with $R_a \approx 0.10$ shows an excellent high resistance against corrosion. On the other hand, cold-rolled AA8015-alloy with $R_a \approx 0.04$ µm shows a higher $R_p$ value (21.923 kΩ) than the low $R_p$ value (9.088 kΩ) of the cold-rolled AA8015 with $R_a \approx 1.54$ µm. This indicates that the former has a stronger resistance to corrosion than the latter.

In a nutshell, the higher the $R_p$ values, the higher the resistance to corrosion. It is also important to note that the cold-rolled AA8015-alloy $R_p$ values are lower than the hot-rolled values, which confirms the effect of strain hardening, except for the cold-rolled AA8015 with $R_a \approx 1.54$ µm; that is probably due to the surface condition of the hot-rolled alloy. Furthermore, the corrosion rates computed for the hot- and cold-rolled AA8015-alloy in natural sea water at different surface roughness values confirms that high $R_p$ values exhibit lower corrosion rates, and vice versa. In addition, as the surface roughness of both the hot- and the cold-rolled AA8015-alloy reduces (or becomes smoother), the rate of corrosion decreases.

Moreover, a significant observation indicates that the corrosion rates for the different surface roughness values in hot-rolled AA8015-alloy are higher than those of the cold-rolled AA8015-alloy; concluding thereby that cold-rolled AA8015-alloy exhibits a lower resistance to corrosion in natural sea water – even at different surface roughness than the hot-rolled AA8015-alloy. This also confirms the strain-hardening effect on the aluminium alloy.
Table 4-22: Summary of the mean values of polarization resistance and corrosion rates of hot-rolled AA8015-alloy at different surface roughness values

<table>
<thead>
<tr>
<th>Surface roughness, $R_a$ (µm)</th>
<th>Polarization resistance, $R_p$ (kΩ)</th>
<th>Corrosion rate, (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.37</td>
<td>4.244</td>
<td>0.035023</td>
</tr>
<tr>
<td>0.65</td>
<td>9.689</td>
<td>0.020553</td>
</tr>
<tr>
<td>0.19</td>
<td>12.399</td>
<td>0.017381</td>
</tr>
<tr>
<td>0.10</td>
<td>28.860</td>
<td>0.006894</td>
</tr>
</tbody>
</table>

Table 4-23: Summary of the mean values of polarization resistance and corrosion rate of cold-rolled AA8015-alloy at different surface roughness values

<table>
<thead>
<tr>
<th>Surface roughness, $R_a$ (µm)</th>
<th>Polarization resistance, $R_p$ (kΩ)</th>
<th>Corrosion rate, (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.54</td>
<td>9.088</td>
<td>0.01289</td>
</tr>
<tr>
<td>0.83</td>
<td>9.336</td>
<td>0.012825</td>
</tr>
<tr>
<td>0.18</td>
<td>11.165</td>
<td>0.0123705</td>
</tr>
<tr>
<td>0.04</td>
<td>21.923</td>
<td>0.006247</td>
</tr>
</tbody>
</table>

Consequently, the weight analysis observed for the hot- and the cold-rolled AA8015-alloys before and after the electrochemical test depict weight gains for the entire samples, in Table 4-24. This explains why corrosion rates are preferably established by mass gain rather than by mass loss.

Table 4-24: Weight analysis of hot- and cold-rolled AA8015-alloy before and after electrochemical corrosion testing

<table>
<thead>
<tr>
<th>Surface roughness condition</th>
<th>Initial weight, $W_i$ (g)</th>
<th>Final weight, $W_f$ (g)</th>
<th>Weight gain, $W_g$ (g)</th>
<th>% weight gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-rolled AA8015 samples at $R_a=1.37$ µm</td>
<td>13.5907</td>
<td>13.5932</td>
<td>0.0025</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>9.2917</td>
<td>9.2963</td>
<td>0.0046</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>9.6877</td>
<td>9.6936</td>
<td>0.0059</td>
<td>0.07</td>
</tr>
<tr>
<td>Hot-rolled AA8015 samples at $R_a=0.65$ µm</td>
<td>8.5494</td>
<td>8.5550</td>
<td>0.0056</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>7.9814</td>
<td>7.9864</td>
<td>0.0050</td>
<td>0.06</td>
</tr>
<tr>
<td>Hot-rolled AA8015 samples at $R_a=0.19$ µm</td>
<td>8.5403</td>
<td>8.5459</td>
<td>0.0056</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>14.1616</td>
<td>14.1708</td>
<td>0.0092</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>9.2954</td>
<td>9.3030</td>
<td>0.0076</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>12.9603</td>
<td>12.962</td>
<td>0.0017</td>
<td>0.01</td>
</tr>
<tr>
<td>Hot-rolled AA8015 samples at $R_a=0.10$ µm</td>
<td>14.0782</td>
<td>14.0858</td>
<td>0.0076</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>13.3689</td>
<td>13.3729</td>
<td>0.0040</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>13.1378</td>
<td>13.1441</td>
<td>0.0063</td>
<td>0.05</td>
</tr>
<tr>
<td>Cold-rolled AA8015</td>
<td>6.3459</td>
<td>6.3467</td>
<td>0.0008</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>5.2218</td>
<td>5.2304</td>
<td>0.0086</td>
<td>0.16</td>
</tr>
</tbody>
</table>
4.4.4 Visual and microstructural observation before and after electrochemical corrosion test

For the examination of the aluminium alloy surfaces, a high mega-pixel camera and TESCAN scanning electron microscope (SEM) with energy dispersive X-ray analysis embedded were used. This was done to determine the nature of the AA8015-alloy damage or attack. Representative camera pictures of the hot- and cold-rolled AA8015-alloy samples at different surface roughness are shown in Figures 4-57 to 4-60. The black spot on the metal surface shows the area and extent of attack on the AA8015-alloy surface immersed in natural sea water after electrochemical corrosion testing at the different surface roughness values considered. The literature reports that aluminium and its alloys have a very high affinity for oxygen when exposed in the presence of air, thereby, acquiring a thin, tightly adhering, protective self-healing inert film of aluminium oxide [197, 198].

It is on the inactivity of this surface film that the good corrosion resistance of aluminium depends. The presence of the black spots confirms that the protective film suffers localized damage or attack under conditions when self-healing of the film cannot occur; thereby, showing localized corrosion taking the form of pitting corrosion in the entire tested AA8015-alloy samples. It is important to note that the black spot density on the AA8015-alloy surface is denser in the hot-rolled samples with surface roughness ($Ra$) 1.37 µm and 0.65 µm than in the cold-rolled samples with surface roughness 1.54 µm and 0.83 µm accordingly. However, an approximate equal concentration of the black spot is observed on the AA8015-alloy surface in the hot-rolled samples with surface roughness ($Ra$) 0.19 µm and 0.10 µm and in the cold-rolled samples with surface roughness values of 0.18 µm and 0.04 µm, respectively.

<table>
<thead>
<tr>
<th>samples at Ra=1.54 µm</th>
<th>8.8885</th>
<th>8.8932</th>
<th>0.0047</th>
<th>0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold-rolled AA8015 samples at Ra=0.83 µm</td>
<td>7.5117</td>
<td>7.515</td>
<td>0.0033</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>6.6303</td>
<td>6.6327</td>
<td>0.0024</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>6.3736</td>
<td>6.3810</td>
<td>0.0074</td>
<td>0.12</td>
</tr>
<tr>
<td>Cold-rolled AA8015 samples at Ra=0.18 µm</td>
<td>11.1519</td>
<td>11.1553</td>
<td>0.0034</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>11.5377</td>
<td>11.5425</td>
<td>0.0048</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>12.3381</td>
<td>12.3414</td>
<td>0.0033</td>
<td>0.03</td>
</tr>
<tr>
<td>Cold-rolled AA8015 samples at Ra=0.04 µm</td>
<td>11.4937</td>
<td>11.4972</td>
<td>0.0035</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>11.2423</td>
<td>11.2483</td>
<td>0.0060</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>11.6342</td>
<td>11.636</td>
<td>0.0018</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Figure 4-57: Macrographs showing visual observation for hot- and cold-rolled AA8015 samples at Ra≈1.37 and 1.54 µm respectively. (a, b) images before corrosion for hot- and cold-rolled samples respectively; (c, d) images after corrosion for hot- and cold-rolled samples respectively

Figure 4-58: Macrographs showing visual observation for hot- and cold-rolled AA8015 samples at Ra≈0.65 and 0.83 µm respectively. (a, b) images before corrosion for hot- and cold-rolled samples respectively; (c, d) images after corrosion for hot- and cold-rolled samples respectively
Likewise, SEM/EDS images of the AA8015-alloy samples were obtained before and after electrochemical corrosion tests. The EDS elemental map spectrum before corrosion shown in Figure 4-61 indicates the presence of an inert aluminium oxide film on the surface of the rolled AA8015-alloy.
Figures 4-62 to 4-69 show the SEM images of the hot- and cold-rolled AA8015-alloy sample surfaces for each surface roughness in consideration. Vivid observation confirms the mode of corrosion as pitting. Moreover, important inspection in the SEM images of the hot-rolled AA8015 samples at $R_a \approx 1.37 \, \mu\text{m}$ and cold-rolled AA8015 samples at $R_a \approx 1.54 \, \mu\text{m}$ show localized damage in the form of pits without the presence of an insoluble substrate known as rust. Further EDS elemental analysis shown in Figure 4-70, reveals the appearance of minute sulphur peaks in the spectrum, indicating some sort of soluble sulphate complex formed on the surface. Additionally, SEM images for other surface roughness considered for both hot- and cold-rolled AA8015-alloy show the substantial presence of an insoluble substrate. The presence of sulphur peaks in the EDS spectra in Figure 4-71, point out the existence of insoluble sulphate complexes formed on the surface during corrosion.
Figure 4-62: SEM images of corroded hot-rolled AA8015 sample at Ra≈1.37 µm. (a) image before corrosion at 271-x magnification; (b-d) images after corrosion at increased magnifications.

Figure 4-63: SEM images of corroded hot-rolled AA8015 sample at Ra≈0.65 µm. (a) image before corrosion at 267-x magnification; (b-d) images after corrosion at increased magnifications.
Figure 4-64: SEM images of corroded hot-rolled AA8015 sample at Ra≈0.19 µm. (a) image before corrosion at 362-x magnification; (b-d) images after corrosion at increased magnifications

Figure 4-65: SEM images of corroded hot-rolled AA8015 sample at Ra≈0.10 µm. (a) image before corrosion at 254-x magnification; (b-d) images after corrosion at increased magnifications
Figure 4-66: SEM images of corroded cold-rolled AA8015 sample at Ra≈1.54 µm. (a) image before corrosion at 314-x magnification; (b-d) images after corrosion at increased magnifications

Figure 4-67: SEM images of corroded cold-rolled AA8015 sample at Ra≈0.83 µm. (a) image before corrosion at 209-x magnification; (b-d) images after corrosion at increased magnifications
Figure 4-68: SEM images of corroded cold-rolled AA8015 sample at Ra≈0.18 µm. (a) image before corrosion at 219-x magnification; (b-d) images after corrosion at increased magnifications.

Figure 4-69: SEM images of corroded cold-rolled AA8015 sample at Ra≈0.04 µm. (a) image before corrosion at 246-x magnification; (b-d) images after corrosion at increased magnifications.
Figure 4-70: (a) SEM image showing pitting corrosion of rolled AA8015-alloy immersed in sea water. (b-e) EDS spectra showing the elemental composition of the selected precipitates (spectrums 1-4) respectively.
Figure 4-71: (a) SEM image showing presence of insoluble substrate on rolled AA8015-alloy surface after corrosion. (b-e) EDS spectra showing the elemental composition of the selected precipitates (spectrum 1-4) respectively
PART B: RESULTS AND DISCUSSION OF THE COLD-ROLLING PROCESS MODELLING AND SIMULATION

4.5 2-D and 3-D finite element simulation results

4.5.1 Contact friction force distribution

The contact frictional force occurs because of the deformation of the plate surface in contact with the work roll under the rolling load. The frictional force distribution on the AA8015 plate surface in contact with the upper work roll during the rolling motion can be seen in the simulated model pictures for the four pass schedules in both 2-D and 3-D FE models in Figures 4-72 and 4-73. The neutral zone (no-slip zone) occurred in the region close to the exit point of the rolled AA8015 plate. This region can be explained as the point where the speeds of the AA8015 alloy plate/sheet and the work rolls are equal [70]. There exists no friction at this point, showing minimal or no deformation taking place in the region. This confirms the work of Singh [70], stating that the resultant shear stress at this point is zero with equal stress components in the opposite direction. The distribution of the contact frictional force on the AA8015-alloy plate surface can be visibly explained with the 3-D model picture. To the left of the neutral point, the contact frictional force spread shows increasing values that allow the drive of the plate in the direction of the work roll rotation. While to the right of the neutral point, the contact frictional force spread opposes the direction of the work roll rotation, where high amounts of deformation are seen to be experienced at the surface of the plate.

![Contact frictional force distribution](image)

Figure 4-72: 2-D FE Model pictures showing contact frictional force distribution (vertical scale bar) in the roll bite during the cold-rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4
In addition, the nodal contact frictional variation time histories for particular nodes 164, 226, 396, and 289 located at the edge surface of the Al 8015 alloy plate/sheet for 2-D FE model, shown in Figure 4-74, were examined. Likewise in Figure 4-75, showing nodes 50, 52, 74 and 7 located at the edge surface of the alloy plate/sheet for 3-D FE model. The contact frictional force steadily increased as the entry point of the AA8015 plate/sheet until it gets to a point (close to the exit) where it drops and picks up again to a higher magnitude before exiting the roll gap. The lowest point at which the magnitude of contact frictional force drops in 2-D FE model and 3-D FE model is significant and approximately zero. This confirms the point of no slip or the neutral point, showing that the magnitude of contact frictional force acting ahead of the neutral point is higher than the one beyond the neutral point.
4.5.2 Plastic strain rate distribution

The plastic deformation in AA8015-alloy during cold-rolling at the roll-bite are shown in Figures 4-76 and 4-77 in 2-D FE models and 3-D FE models, respectively. The sequence of material flows through the roll gap for each pass is revealed. There exist interesting interactions between the deformation of the surface and the deformation in the centre of the plate/sheets for each pass. When deformation takes place on the surface, the centre part is relatively undeformed and vice versa. Likewise, the rate of deformation shifts from high to low in a cross-like pattern and diminishes towards the exit gap particularly close to the neutral zone. Subsequent in-depth analysis shows varying distinct plateaux/regions along the contact length for each pass in the nodal variation plastic strain rate plot in Figures 4-78 and 4-79. These distinct plateaux or regions can also be confirmed in the equivalent plastic strain rate model pictures in Figures 4-76 and 4-77,
respectively; concluding thereby that deformation takes place in steps in a uniform cross-like pattern through the roll gap. In addition in Figures 4-78 and 4-79, the plastic strain rate during deformation increases with per cent cold work or the thickness reduction for both the 2-D and 3-D FE simulations.

![Figure 4-76: 2-D FE Model pictures showing plastic strain rate distribution (vertical scale bar) in the roll bite during the cold-rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4](image)

![Figure 4-77: 3-D FE Model pictures showing plastic strain rate distribution (vertical scale bar) in the roll bite during cold-rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4](image)
4.5.3 Equivalent Von Mises Stress distribution

Figures 4-80 and 4-81 shows the Von Mises stress distribution in the roll-bite for each pass schedule. A steady increase in Von Mises stress is observed for each successive thickness reduction. This is evident in the colour contour regions in the rolled plate/sheet for the four pass schedules.
Figure 4-80: 2-D FE Model pictures showing equivalent Von Mises stress distribution (vertical scale bar) in the roll bite during cold-rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4.

Figure 4-81: 3-D FE Model pictures showing equivalent Von Mises stress distribution (vertical scale bar) in the roll bite during the cold rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4.

In addition, Figures 4-82 and 4-83 for the 2-D and 3-D FE models respectively, confirm that Von Mises stress increases with the plastic strain during cold-rolling. Significant observation shows increasing
magnitude of Von Mises stress, as the gauge thickness of the AA8015 plate is reduced successively. A slight increment is shown to occur for passes 3 and 4 due to the minimal amount of cold work it underwent.

Figure 4-82: Equivalent Von Mises stress vs plastic strain for the four pass schedules at the roll-strip interface in 2-D FE models

Figure 4-83: Equivalent Von Mises stress vs plastic strain for the four pass schedules at the roll-strip interface in 3-D FE models
4.5.4 Normal and shear stress distribution

Further insight into the normal and shear stress distribution during the deformation process of AA8015-alloy is discussed. The transverse load of the work roll on the AA8015-alloy plate/sheet causes deformation that induces normal stress and shear force that induces shear stress. Figures 4-84 and 4-85 depict the model pictures of the normal and shear stress distribution in the alloy plate/sheet during the deformation process for the 2-D FE models. The normal stresses vary along the length and centre/ mid-thickness of the AA8015 plate/sheet during rolling; while the shear stresses along the alloy plate/sheet length. However, for the 3-D FE models, the normal and shear stress is seen to vary in the width spread at the roll-strip interface showing much effect of the stresses at the centre/mid-thickness region of the alloy plate/sheet. See Figures 4-86 and 4-87.

Likewise, as explained in the contact frictional force and plastic strain rate distribution in Sections 4.5.1 and 4.5.2, the shear stress distribution in the 2-D and 3-D FE models confirm the neutral or no-slip zone. Subsequently, the presence of the plateau or the deformation pattern on the roll-strip interface along the width spread is shown vividly for the four pass schedules.

Furthermore, the nodal variation time histories for the normal and shear stress in the 2-D and 3-D FE models, shown in Figures 4-88 and 4-89, also confirm the neutral or no-slip zone and the stepwise uniform cross-like pattern through the roll gap.

Figure 4-84: 2-D FE Model pictures showing normal stress distribution (vertical scale bar) in the roll bite during cold-rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4
Figure 4-85: 2-D FE Model pictures showing shear stress distribution (vertical scale bar) in the roll bite during cold-rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4

Figure 4-86: 3-D FE Model pictures showing normal stress distribution (vertical scale bar) in the roll bite during cold-rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4
Figure 4-87: 3-D FE Model pictures showing shear stress distribution (vertical scale bar) in the roll bite during cold-rolling of AA8015-alloy (a) Pass 1; (b) Pass 2; (c) Pass 3; and (d) Pass 4

Neutral or No-slip

Figure 4-88: Nodal normal and shear stress variation-time histories for the four pass schedules at the roll-strip interface for 2-D FE models
4.5.5 Roll separating force and roll torque

In the rolling operations of any metallic material, the yield stress of the rolled material affects the roll separating force and the torque. Figures 4-90 and 4-91 depict the 2-D and 3-D FE simulation results of the roll-separating force and the torque respectively. It may be presumed from the results that the ramp-up in the roll separating force (the region before it reaches the steady state) shows a consistent increase from Pass 1 to Pass 4. This ramp-up can be explained from the viewpoint of initial contact with the work roll. There exists plastic deformation almost directly after the initial contact. This plastic part of the plate/sheets increases in size – until the point when a few sections of the plate/sheets exit the roll gap leading to a steady state rolling. Also, the ramp-up in the roll force increases as long as the contact length increases. Moreover, the slight fluctuation or damping behaviour in the roll-separating force and the roll torque, which is obvious in the 3-D FE model when the deformation is in a steady state is expected. The reason being that the values vary over a certain range; and they are not always constant, due to the dynamics of the rolling process in the rolling industry. However, in the simulation, it is as a result of numerical disturbance created by the contact algorithm and the mesh discretization. It is important to note that the variances in history time for each pass are according to the different roll speeds designated and also a function of the arc length of contact. Equally important is the steady increase in the roll-separating force for both 2-D and 3-D results from Pass 1 to Pass 3 (from 4.74 MN to 5.48 MN for 2-D models and 4.72 MN to 5.46 MN for 3-D models) respectively. Followed by just over 5.48 MN in Pass 4 and a slight decrease to 5.44 MN in Pass 4 for the 2-D and 3-D models, respectively. However, the designer/operator of the roll schedule sometimes intends this.

In addition, the roll-separating force is also dependent on the yield strength of the rolled material and the contact length. The amount of cold work for each pass schedule is a function of the yield stress and
indirectly also a function of the roll-separating force. Decisively, the higher the material stiffness and the area reduction, the higher the roll-separating force.

A significant part of the simulation discussion for the roll-separating force also applies to the roll torque, utilizing residual force or displacement convergence criteria with a tolerance of 0.001. However, the roll torque magnitude for the four passes is not consistent, due to the varying contact length made for each plate/sheets with the rolls.

Figure 4-90: 2-D FE Model time histories for each pass schedule showing (a) roll separating force and (b) roll torque values
Figure 4-91: 3-D FE Model time histories for each pass schedule showing (a) roll separating force and (b) roll torque values.

4.5.6 Validation of roll-separating force

Figure 4-92 shows a comparison of the roll-separating forces for both the predicted (2-D & 3-D) and industrial data for each of the passes. There exist good correlations between the predicted and industrial roll-separating force for the passes except for pass 4. The first pass with 36% reduction gave a close value with an error margin of approximately 1%; while subsequent passes show error margins in the region of 4%, 6%, and 30%, respectively. The higher percentage error exhibited in pass 4 can be explained from the viewpoint of increased friction along the arc length of contact; since the contact length or the contact area increases with the thickness reduction. This revealed that the frictional forces varied for each roll pass. Therefore, it may be deduced that the friction coefficient of the frictional force is not constant along the arc length of contact for each per cent reduction.
Coupled thermo-mechanical 2-D finite element simulation results

Coupled thermo-mechanical 2-D FE simulations of the cold-rolling process of AA8015-alloy were accomplished for four subsequent pass schedules in a 4-high stand cold-rolling mill. Both deformable-rigid and deformable-deformable contact algorithms were investigated for all the pass schedules to investigate the effect of thermal influence on the process parameters in the strain-hardening process. The results obtained revealed the same characteristics with the contact-friction force, the plastic strain rate, the equivalent Von Mises and the normal and shear stress, as seen earlier in the 2-D FE simulation without consideration of thermal analysis in section 4.5. Despite this replica in characteristics, some significant observations were identified and inferred for each of the parameters.

4.6.1 Contact friction-force distribution

The neutral or no-slip region was also confirmed in both the deformable-rigid and the deformable-deformable contact algorithms, as shown in Figures 4-93 and 4-94, respectively. Although, the neutral or no-slip zone characterized with negligible or zero contact frictional force is clearly visible in the deformable-deformable contact algorithm. Similarly, the nodal contact friction force variation graphs in Figures 4-95 and 4-96 show a replica of the 2-D FE simulation results without thermal consideration (see Figure 4-74). However, the contact frictional force magnitude range in the coupled thermo-mechanical FE simulation for both algorithms in all the four pass schedule are lower, which is due to the effect of energy exchange, as a result of heat.
Figure 4-93: Pictures showing contact friction force distribution (vertical scale bar) in the roll bite for deformable-rigid contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work)

Figure 4-94: Pictures showing contact friction force distribution (vertical scale bar) in the roll bite for deformable-deformable contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work)
4.6.2 Plastic strain rate distribution

The plastic strain rate distribution for the couple thermal/structural analysis in both contact algorithms is depicted in Figures 4-97 and 4-98. Also, the rate of deformation shifts from high to low in a cross-like pattern; and it diminishes towards the exit of the roll gap. Distinct plateaux/regions along the contact length for each pass were also confirmed. In Figures 4-99 and 4-100, the nodal plastic strain rate variations also show a replica, although with lower magnitude for all the passes compared to Figures 4-78.
Figure 4-97: Pictures showing plastic strain rate distribution (vertical scale bar) in the roll bite for deformable-rigid contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work)

Figure 4-98: Pictures showing plastic strain rate distribution (vertical scale bar) in the roll bite for deformable-deformable contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work)
4.6.3 Equivalent Von Mises stress

The equivalent Von Mises stress distribution for the coupled thermo-mechanical analysis, in Figures 4-101 and 4-102 for deformable-rigid and deformable-deformable contact algorithms respectively, shows nearly equal colour-contour distributions in the model pictures, except for pass 1 (compare Figures 4-80 and 4-81). This is due to the higher amount of heat generated as a result of the high initial temperature input compared to the other passes. Further investigation shows equivalent magnitudes in the Von Mises stress during the deformation process, except for pass 1.
4.6.4 Normal and shear-stress distribution

The effect of the transverse load of the work roll and the shear force for the coupled thermo-mechanical analysis in deformable-rigid and deformable-deformable contact algorithms is shown in Figure 4-103 to Figure 4-106. The normal and shear stress are non-uniformly distributed along the deformed AA8015
plate/sheet length at the roll-strip interface during rolling. Likewise, the effect of the transverse loading is seen to vary at the centre/mid-thickness of the deformed AA8015 plate/sheet during rolling. The thermal effects of the coupled thermo-mechanical simulation investigated show that normal stress magnitudes are significantly lower compared to the 2-D FE simulation, without any consideration of the thermal input. Further observation reveals a higher shear stress magnitude (see Figures 4-107 and 4-108 in comparison with Figure 4-88). Deducing that the thermal analysis of cold rolling process has a significant impact on the normal and shear stress during the rolling process.

Figure 4-103: Pictures showing normal stress distribution (vertical scale bar) in the roll bite for deformable-rigid contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work)
Figure 4-104: Pictures showing shear stress distribution (vertical scale bar) in the roll bite for deformable-rigid contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work)

Figure 4-105: Pictures showing normal stress distribution (vertical scale bar) in the roll bite for deformable-deformable contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work)
Figure 4-106: Pictures showing shear stress distribution (vertical scale bar) in the roll bite for deformable-deformable contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work)

Figure 4-107: Nodal normal and shear stress variation-time histories for the four pass schedules at the roll-strip interface deformable-rigid contact algorithm
4.6.5 Heat flux distribution

In general, heat flux is associated with heat transport from a high-temperature region to a low-temperature region [199]. Consequently, heat flows from the rolled plate/sheet with the higher temperature to the work roll with a colder ambient temperature. This is visible in the 2-D FE model simulated picture using the deformable-deformable contact algorithm, shown in Figure 4-110 for each per cent cold work. However, in the deformable-rigid contact algorithm, presented in Figure 4-109, heat flows from the rolled plate/sheet to the rigid work roll; but it is being repelled due to the geometric nature of the roll modeling compared to the deformable roll model in the deformable-deformable contact algorithm. This is evident in the high heat flux recorded in the nodal heat flux variation for each pass (except for pass 1) at the roll-strip interface for deformable-rigid contact algorithm as compared to the deformable-deformable contact algorithm, shown in Figure 4-111.

It is important to note that the intensity of the heat flow is high at the roll-strip interface for pass 1; and it reduces with subsequent passes, as the gauge thickness of the plate is reduced.

In addition, the rate of deformation of AA8015 alloy during the cold-rolling process for each pass affects the amount of heat generated by deformation, which in turn affects the heat flux. The heat flux simulated pictures in Figures 4-109 and 4-110 for both contact algorithms also confirm the stepwise cross-like pattern. However, the cross-like pattern vanishes nearly at the neutral point. Moreover, the heat flow to the work roll decreases, as the sheet thickness reduces.
Figure 4-109: Pictures showing heat flux distribution (vertical scale bar) in the roll bite for deformable-rigid contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work)

Figure 4-110: Pictures showing heat flux distribution (vertical scale bar) in the roll bite for deformable-deformable contact algorithm (a) Pass 1 (36% cold work); (b) Pass 2 (24% cold work); (c) Pass 3 (29% cold work); and (d) Pass 4 (32% cold work)
4.6.6 Temperature distribution

The temperature distribution of the AA8015 plate at each pass schedule for the deformable-rigid and deformable-deformable contact formulations is shown in Figures 4-112 and 4-113 respectively.

Figures 4-112 and 4-113 show the heat/temperature steadily increases in the roll bite for each pass. The temperature increase starts at the initial contact between the rolled material and the work roll; and it reaches the maximum temperature near the neutral zone. After the neutral zone, the temperature is fairly steady all the way to the exit of the roll gap. The highest temperature attained spread from the centre/ mid-thickness of the rolled plate/sheet for the passes. However, in Figure 4-112(a) depicting temperature distribution in pass 1 shows a different temperature contour pattern, with the highest intensity noticeable in a cone-like pattern beginning from the midpoint of the roll-bite zone, at the centre/mid-thickness of the plate. This prevails to just a little beyond the exit point at symmetry line of the plate. This is caused by the difference in the initial temperature of the plate, which may have a tribological effect at the roll-strip interface. Furthermore, the temperature distribution for the deformable-deformable contact, see Figure 4-113, shows few colour-contour regions in the rolled plate/sheet for the four passes. Temperature loss from the rolled plate/ sheet to the rolls is obvious. The work roll in pass 1 shows a significant temperature increase. This is due to the elevated temperature of the workpiece, the heat generated by the plastic deformation of the workpiece and the heat generated by sliding on the roll-strip interface.
For in-depth investigation in the trend of temperature change in the cold-rolling process, a node-tracking analysis of the nodal temperatures at the rolled plate/sheet surface having an interface with the work roll was extricated from the simulation outcome data, depicted in Figure 4-114. It is necessary to mention that the trend in nodal temperature change for the nodes at the plate/sheet surface in contact with the work roll in each pass schedule is the same for all the nodes. For both contact algorithms, there exists an identical
trend in the nodal temperature variation for the four passes investigated. The trend in temperature rise at the roll-bite shows a sudden stepwise increase; and it becomes steady from the roll gap exit. However, the temperature rise in the deformable-deformable contact algorithm reaches a lower degree at the steady state for the four passes compared to the deformable-rigid contact algorithm. This is due to the heat loss to the deformable work roll compared to the rigid roll developed in the 2-D finite element models. In addition, as the plate/ sheet exits the roll gap, the temperature shows a slight decrease due to the heat loss to the environment for both of the two contact algorithms. Nevertheless, the effect of the temperature decrease is seen in the deformable-deformable contact algorithm. Likewise, the trend in nodal temperature rise increases from pass 1 to pass 4, with an approximate per cent temperature increase of 10%, 26%, 40% and 49%, respectively. The low percentage in the temperature increase exhibited in pass 1 further explains the difference in the temperature-contour pattern occurrence.

![Nodal temperature variation -time histories for each pass at roll-strip interface](image)

**Figure 4-114:** Nodal temperature variation -time histories for each pass at roll-strip interface (a) deformable-rigid contact algorithm; and (b) deformable-deformable contact algorithm

### 4.6.7 Roll-separating force and roll torque

The roll-separating force and torque results obtained from the coupled thermo-mechanical finite element simulation for the deformable-rigid and for the deformable-deformable contact algorithm are plotted in Figures 4-115 and 4-116, respectively. A replica in the characteristics in the time histories plot for both the roll separating force and the roll torque is revealed compared to the 2-D FE simulation, without consideration of thermal analysis in Figure 4-90. However, the varying magnitude of the roll-separating force and the roll torque was observed, due to the thermal analysis. Table 4-25 reveals the magnitudes of the roll separating force and the roll torque for both the deformable-rigid and the deformable-deformable contact algorithms.
Figure 4-115: Coupled thermo-mechanical 2-D FE Model time histories for each pass schedule in deformable-rigid contact algorithm showing (a) roll separating force and (b) roll torque values.
Figure 4-116: Coupled thermo-mechanical 2-D FE Model time histories for each pass schedule in deformable-deformable contact algorithm showing (a) roll separating force and (b) roll torque values.

Table 4-25: Predicted roll separating force and roll torque magnitudes for coupled thermo-mechanical 2-D FE model simulation

<table>
<thead>
<tr>
<th>Pass Schedule</th>
<th>Deformable-rigid contact algorithm</th>
<th>Deformable-deformable contact algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roll separating force (MN)</td>
<td>Roll torque (kNm)</td>
</tr>
<tr>
<td>Pass 1</td>
<td>4597130</td>
<td>-43960.23</td>
</tr>
<tr>
<td>Pass 2</td>
<td>4768275.6</td>
<td>-31623.4</td>
</tr>
<tr>
<td>Pass 3</td>
<td>5030352.6</td>
<td>-32445.3</td>
</tr>
<tr>
<td>Pass 4</td>
<td>4521677.6</td>
<td>-25250.9</td>
</tr>
</tbody>
</table>
4.6.8 Validation of roll separating force

The calculated roll separating force from the two contact algorithms used has been compared with the measured roll force in the industrial rolling mill; and this is shown in Figure 4-117. The varying coefficient of friction for each pass utilized, coupled with the thermal influence, also shows good agreement with the industrial data. The calculated error margin for pass 1 is about 1.5% less than the industrial value. In pass 2, it is 0.5% higher; while in pass 3 it is 2.1% lower; and in pass 4 it is 15.7% higher. To get accurate finite element results, accurate experimental examination of the tribological conditions at the interface is important, together with a validation of the numerical approach. This is especially necessary between the steel and aluminium contact bodies for each pass.

![Figure 4-117: Predicted roll-separating force compared with industrial data at varying pass schedule/ percentage of the cold work](image)

4.7 Summary

This chapter has presented the findings for the experimental investigation for hot- and cold-rolled AA8015-alloy, as well as the finite-element modelling and simulation of the cold-rolling process. Two-dimensional and three-dimensional finite element models were developed for the four pass schedules; and the rolling process was simulated. Furthermore, the coupled thermo-mechanical analysis was performed for the two contact algorithms: deformable-rigid and deformable-deformable contact, which examined the effect of the energy exchange as a result of heat. The findings are briefed.
The results obtained from the mechanical, metallography and electrochemical corrosion testings are summarized as follows:

1. The reversing and the non-reversing cold-rolled AA8015-alloy sheet samples all showed improved strengths and enhanced hardness properties with a reduced amount of ductility compared to the hot-rolled AA8015 sample. Moreover, for the non-reversing cold-rolled AA8015 sheet samples of varying gauge thickness, the strengths, hardness and the amount of ductility increases with per cent cold work; but it starts to decrease when the gauge thickness is ≤ 1 mm.

2. Microstructural observation for the hot-rolled, reversing cold-rolled and non-reversing cold-rolled AA8015-alloy samples all show an equiaxed grain structure. Microstructural observation for the hot-rolled AA8015-alloy sample in the longitudinal and transverse section rolling direction reveals densely populated smaller grains in the transverse section when compared to the longitudinal section. Further investigation into the microstructure of the reversing and the non-reversing cold-rolled AA8015-alloy sheet samples is interesting. The reversing cold-rolled AA8015 sample also confirms higher grain size in the longitudinal section, when compared to the transverse section. The average grain size in the longitudinal section is approximately twice larger than the hot-rolled grains. This is due to the strain hardening effect on the rolling surface. Likewise, in the transverse section, the larger grains are revealed compared to the hot-rolled sample grains. Moreover, the non-reversing cold-rolled AA8015-alloy sheet samples with different per cent cold work or gauge thickness were examined. The average grain size measured in both the longitudinal and transverse sections decreases with per cent cold work or the gauge thickness, except for an observed increment in the average grain size of 1 mm gauge thickness in the cold-worked sample. The presence of bright particles in the SEM images for all the samples was also observed. The EDS analysis shows Manganese (Mn) atoms heterogeneously present in solid solution in the aluminium matrix.

3. Electrochemical corrosion examination of the hot- and cold-rolled AA8015-alloy at different degrees of surface roughness in natural sea water reveals the following outcome:
   a) Open circuit potential $E_{oc}$ values of the cold-rolled samples are more electronegative in comparison with the hot-rolled samples in natural sea water. Thus, proposing that cold-rolled AA8015-alloy has a greater tendency to oxidize.
   b) The polarization curves obtained for all the hot- and cold-rolled AA8015 samples show asymmetric curves with evidence of pitting corrosion suggested due to the noisy electrode response.
   c) Surface roughness affects the corrosion resistance of both hot- and cold-rolled AA8015-alloy in natural sea water.
d) Polarization resistance \( (R_p) \) of the cold-rolled AA8015-alloy samples has lower values than the hot-rolled samples; this confirms the effect of strain hardening.

e) Cold-rolled AA8015-alloy exhibits lower resistance to corrosion in natural sea water at varying degrees of surface roughness than does the hot-rolled AA8015-alloy.

f) The presence of the black spots confirms that the protective film suffers localized damage under conditions were the self-healing of aluminium oxide film cannot occur.

g) EDS elemental analysis reveals the existence of insoluble sulphate complexes formed on the surface during corrosion.

Additionally, the cold-rolling process modelling and simulation findings are further summarized as follows:

1. AA8015-alloy behaviour during strain hardening process for the two-dimensional and three-dimensional finite element simulation has confirmed the neutral or no-slip zone in the region close to the exit point of the rolled AA8015 plate/sheet. This is established in the plastic strain rate and shear stress distribution in the simulated model pictures. The neutral or no-slip zone is mainly explained in the literature theoretically.

2. The AA8015-alloy during the deformation process shows that the rate of deformation shifts from high to low in a cross-like pattern and diminishes towards the exit gap, particularly close to the neutral zone. This concludes that deformation takes place in a stepwise manner through the roll gap.

3. The equivalent Von Mises stress increases as the gauge thickness of the AA8015 plate is strain-hardened successively.

4. The predicted roll-separating forces and torques from the simulated two-dimensional and three-dimensional finite element models are almost equivalent. The predicted roll-separating force shows good correlation with the industrial computed data. However, the fourth pass schedule varies with an error margin of 30%.

5. The effect of energy exchange, as a result of the heat input to the finite element simulation in the coupled thermo-mechanical analysis has shown a lower magnitude of contact frictional force, plastic strain rate, and normal stress; and higher shear stress magnitude in the roll bite of the strain-hardened AA8015-alloy when compared to the two-dimensional finite element simulation, without consideration of the thermal input.

6. Likewise, the predicted roll-separating force from the deformable-rigid and the deformable-deformable contact algorithm finite element simulations reveals a better agreement with the industrial measurement, except for pass 4, which is probably due to the increased friction along the arc length of contact at the roll-strip interface.
7. The deformable-deformable contact algorithm is necessary for adequate examination of the work roll during the rolling operation. It accurately predicts the temperature distribution in the work roll, to help facilitate the needed design strategies for an efficient cooling system and work roll design. In addition, the temperature distribution in the roll bite rises steadily in a stepwise manner. This thermal rise might induce a significant amount of localized stress within the work roll, which could promote the level of dimensional imprecision of the finished rolled product or reduce the work roll lifespan due to inherent defects, such as roll-surface cracking and spalling.

The succeeding chapter presents the general conclusions; and it makes some suggestions for future work.
CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Introduction
This chapter introduces the general conclusions of the research and suggestions for future work. The conclusions were outlined based on the mechanical and metallography test; electrochemical corrosion test; 2-D and 3-D finite element simulation and coupled thermo-mechanical finite element analysis of the rolling process of AA8015-alloy.

5.2 General conclusions
This thesis has focused on experimental investigations into the hot- and cold-rolled AA8015-alloy behavioural properties, and the cold-rolling system finite element modelling and simulation of the alloy strain-hardening process. The following conclusions can be drawn:

5.2.1 Mechanical and metallography test
1. The reversing and non-reversing cold-rolled AA8015-alloy sheet samples all showed improved strengths and enhanced hardness properties, with a reduced amount of ductility compared to the hot-rolled AA8015 sample. Moreover, for the non-reversing cold-rolled AA8015 sheet samples of varying gauge thickness, the strengths, the hardness and the amount of ductility increases with per cent cold work; but it starts to decrease when the gauge thickness is equivalent to and less than 1 mm.

2. Microstructural observation of the hot-rolled, reversing cold-rolled and non-reversing cold-rolled AA8015-alloy samples all show an equiaxed grain structure.

3. For the non-reversing cold-rolled AA8015-alloy, the average grain size measured in both the longitudinal and the transverse sections decreases with per cent cold work or the gauge thickness, except for an observed increment in the average grain size of 1 mm gauge thickness for the cold-worked sample.

4. The mechanical and microstructural study for the hot-rolled, reversing cold-rolled and non-reversing cold-rolled AA8015-alloy concludes that the cold-worked alloy is preferable in most commercial applications of AA8015-alloy. This is due to its improved strength and enhanced hardness properties, as a result of the strain-hardening effect and its apparent closer dimensional tolerances and a wider range of surface finish.
5.2.2 Electrochemical corrosion test

1. Open-circuit potential values of the cold-rolled samples are more electronegative in comparison with the hot-rolled samples in natural sea water. Thus, proposing that cold-rolled AA8015-alloy has a greater tendency to oxidize.

2. Surface roughness affects the corrosion resistance of both the hot- and cold-rolled AA8015-alloy samples in natural sea water. In addition, the polarization resistance of the cold-rolled AA8015-alloy samples has lower values than those of the hot-rolled samples. This confirms the effect of the strain-hardening.

5.2.3 2-D and 3-D Finite Element Simulation of rolling process of AA8015-alloy

1. AA8015-alloy behaviour during the strain-hardening process for the 2-D and 3-D finite element simulation has confirmed the neutral or no-slip zone in the region close to the exit point of the rolled AA8015 plate/sheet. This is established in the plastic strain rate and in the shear stress distribution in the simulated model pictures. The neutral or no-slip zone is mainly explained theoretically in previous research. In Chapter 2, a literature review on the neutral or no-slip zone is presented.

2. The AA8015-alloy during the deformation process shows that the rate of deformation shifts from high to low in a cross-like pattern; and it diminishes towards the exit gap, particularly close to the neutral zone. It may be concluded that the deformation takes place in a stepwise manner through the roll gap.

3. The predicted roll-separating forces for the four pass schedules have been validated with industrial measurement and have shown good correlation, except for the fourth pass schedule that deviates with a larger error margin.

5.2.4 Coupled thermo-mechanical finite element analysis

1. The effect of energy exchange, as a result of heat input to the finite element simulation in the coupled thermo-mechanical analysis has shown a lower magnitude of contact frictional force, plastic strain rate, and normal stress. Also, higher shear stress magnitudes were observed in the roll bite of the strain-hardened AA8015-alloy when compared to the two-dimensional finite element simulation (without consideration of thermal input).

2. The deformable-deformable contact algorithm is necessary for adequate examination of the work roll during the rolling operation. It accurately predicts the temperature distribution in the work roll, to help facilitate the needed design strategies for an efficient cooling system and work-roll design. In addition, the temperature distribution in the roll bite rises steadily in a stepwise manner. This thermal rise might induce a significant amount of localized stresses within the work roll. These
stresses could promote the level of dimensional imprecision of the finished rolled product or reduce the work roll lifespan due to inherent defects, such as roll-surface cracking and spalling.

5.3 Recommendations for future work

For further experimental work on the electrochemical corrosion of rolled AA8015-alloy, it is recommended that different electrolyte solutions be used for other typical applications. Increased understanding on the corrosion behaviour of Aluminium could be important in other industries, such as the food-packaging industry where aluminium foils are used. Electrochemical corrosion testing could be performed on Aluminium foil material (AA8015-alloy) in a closed system prototype consisting of liquids replicating human stomach fluids.

Further suggestions include:

1. The same experimental study should be performed on heat-treated AA8015-alloy samples to examine the effects of the heat treatment.
2. Study the corrosion behaviour of AA8015-alloy at different temperatures in a closed system, without environmental interference, or any exposure to atmospheric air.
3. The effect of roll-bending on the rolls in the cold-rolling process should be investigated.
4. Cold-rolling system modelling and simulation should be expanded to examine and profound solutions to chatter vibrations, which limits the speed of production in rolling mills.
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APPENDIX A

A1: Some pictures of rolling mill from industrial visit to Tower Aluminium Rolling Mill (TARM) Nigeria Plc, Km 38, Abeokuta Expressway, Sango-Ota, Ogun State, Nigeria

Figure A1-1: Pictures taken when the hot-rolled AA8015-alloy (7mm) stack is fed into the 4-Hi reversing Achenbach Cold Rolling Mill

Figure A1-2: Pictures of the 4-Hi reversing Achenbach Cold Rolling Mill during rolling process of AA8015-alloy
A2: Brief extract from the industrial visit to Tower Aluminium Rolling Mill (TARM) Nigeria Plc, Km 38, Abeokuta Expressway, Sango-Ota, Ogun State, Nigeria

A2-1 Sheet rolling operation
A2-1.1 Breakdown mill
The first rolling mill encountered by an aluminium ingot entering the rolling line is called the “breakdown mill.” It is usually a single-stand four-high reversing hot rolling mill. Its main function is to “break down” the ingot, reducing its thickness to the dimensions of plate. The product of the breakdown mill is fed through additional rolling mills (hot) for further thickness reduction and/or surface finishing. In a breakdown mill, the work rolls are powered and their back-up rolls are turned by contact with the work rolls. The breakdown mill apply a large amount of energy to each work roll to drive the ingot through the gap, where it undergoes a compression force along the contact line. Breakdown mills are often described by the length of the work rolls they can accommodate and consequently the maximum width of product they can roll.

A prepared ingot is sent into the hot rolling mill at a carefully adjusted rolling temperature. The rolling process itself generates additional heat: from friction between the ingot and the work rolls; and from the severe deformation of the metal as its thickness is reduced. This additional heat is removed to maintain
temperature control. This is necessary not only to prevent excessive thermal distortion of the mill rolls but also to control alloy temper throughout the rolling sequence. In addition, the work rolls is also lubricated, to prevent the hot aluminium from sticking to the rolls and causing surface flaws on the product. Both the quantity and application pattern of lubrication is appropriately controlled. A system of hoses feeds liquid coolant/lubricant through the nozzles of spray bars installed in front of the rolls. Lubricant is generally suppressed when the ingot enters the work roll gap, to promote a good friction “bite” by the rolls, and then is applied while the ingot passes through. There is enough lubricant to prevent sticking but not too much for heat removal and lubrication.

The operator manipulates the table rolls (two sets of rollers independently controlled) to position the ingot and start it between the work rolls. Cross rolling is sometimes needed to achieve a specific width. The work rolls draw the ingot through and reduce its thickness. Then the operator narrows the gap a few more inches (centimetres), reverses the mill, and sends the ingot back through it. The ingot is rolled back and forth until it becomes a long slab, of about 7.0mm thick.

A2-1.2 Annealing

The Aluminium cast coil becomes hardened by the hot rolling procedures to a degree that is not desired in the finished product or that would interfere with further rolling and the achievement of a desired temper, in which is cooled to undergo some partial solution heat treatment and precipitation hardening. The annealed cast coil is then cold rolled in 4-Hi reversing Achenbach Cold mill for further thickness reduction.

A2-1.3 The cold-rolling process

Cold rolling is used to give aluminum metal sheet a desired strength and temper, to provide a final surface finish and to reduce sheet to very small thicknesses. For example, aluminium beverage can stock is cold-rolled. This is achieved in five or six passes through a four-high reversible cold mill.

The sheet enters the cold mill at room temperature, the friction and pressure of rolling raises its temperature. This excess heat is removed by an appropriate coolant/lubricant. The first pass through the four-high reversible cold rolling mill reduce the material thickness by about 40 percent. Subsequent passes reduce the thickness by similar or smaller amounts.

To produce a reflective surface on cold rolled sheet, smaller thickness reductions are rolled during the final passes. The brightest surfaces are produced by the use of highly polished work rolls.

The desired reduced sheet thickness is wrapped in a single coil depends on the coil diameter and on the sheet thickness. The wrapped sheet coil is further annealed.
A2-1.4 Further annealing
Cold rolling elongates grains and sets up internal stresses and strain. These changes create resistance to further deformation. The cold-rolled plate or sheet is said to become “work-hardened.” Unwanted precipitation hardening or work hardening is removed before further rolling or product finishing by annealing that is, by heating the aluminium alloy above its recrystallization temperature and holding it there long enough for the grain structures created earlier to re-crystallize and relieve the internal stresses.

A2-1.5 Slitting process
Annealed coiled sheet is then run through a high-speed slitter, whose circular knives trim the edges straight. The slitter may also divide wide sheet into narrower coils of specified widths. The slitter may be used not only to trim the edges of wide sheet, but it may also cut sheet into narrower strips down to widths as small as 1/4 inch (6.3 mm) according to the customer's specifications. The slit sheet is recoiled as it emerges from the slitter. A laser scanner simultaneously checks for surface defects.

A2-1.6 Data collection
The data in the table below shows the readings collected from the computer graphic user interface of the Achenbach cold mill for a cold rolled cast coil that last for almost two hours.

<table>
<thead>
<tr>
<th>COLD-ROLLED CAST COIL</th>
<th>Sheet Input</th>
<th>Sheet Output</th>
<th>Gap Skew (mm)</th>
<th>Differential Load (tons)</th>
<th>Total Load (tons)</th>
<th>Roll-speed L/H (mm)</th>
<th>Bending pressures (bars)</th>
<th>Calculated Gap (mm)</th>
<th>No. of pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>Nominal (mm)</td>
<td>Thickness (mm)</td>
<td>Nominal (mm)</td>
<td>Differential Load (tons)</td>
<td>Total Load (tons)</td>
<td>Roll-speed L/H (mm)</td>
<td>Bending pressures (bars)</td>
<td>Calculated Gap (mm)</td>
<td>No. of pass</td>
</tr>
<tr>
<td>7.0±0.5</td>
<td>7.0</td>
<td>5.0±0.3</td>
<td>4.5</td>
<td>-0.4</td>
<td>24-27</td>
<td>464-467</td>
<td>44</td>
<td>64</td>
<td>103</td>
</tr>
<tr>
<td>5.0±0.3</td>
<td>4.5</td>
<td>3.4±0.05</td>
<td>3.4</td>
<td>-0.4</td>
<td>15-19</td>
<td>470-475</td>
<td>64</td>
<td>98</td>
<td>103</td>
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<tr>
<td>3.4±0.05</td>
<td>3.4</td>
<td>2.5±0.05</td>
<td>2.4</td>
<td>-0.5</td>
<td>28-32</td>
<td>510-514</td>
<td>85</td>
<td>124</td>
<td>103</td>
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<tr>
<td>2.4±0.05</td>
<td>2.4</td>
<td>1.64±0.05</td>
<td>1.64</td>
<td>-0.3</td>
<td>18-21</td>
<td>377-381</td>
<td>145</td>
<td>39</td>
<td>-13</td>
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<tr>
<td>1.64±0.05</td>
<td>1.64</td>
<td>1.3±0.05</td>
<td>1.3</td>
<td>-0.4</td>
<td>27-30</td>
<td>271-283</td>
<td>117</td>
<td>101</td>
<td>-25</td>
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<tr>
<td>1.3±0.05</td>
<td>1.3</td>
<td>0.79±0.05</td>
<td>0.78</td>
<td>-0.3</td>
<td>16-20</td>
<td>265-373</td>
<td>129</td>
<td>84</td>
<td>9</td>
</tr>
</tbody>
</table>

NOTE
Max. Rolling speed =325m/minute (5.42m/s)
Sheet width = 1250mm
Aluminium Four Hi Irreversible Coil Cold Rolling Mill
Material: aluminium, aluminium alloy
Tensile strength: ≤340
Input thickness and width: max 9mm, 800〜1350mm
Input coil specification:
(1) Inner diameter 508mm
(2) Outer diameter: max 1600mm
(3) Max 5T

Finished coils:
(1) Width: 800～1300mm
(2) Thickness: 0.2-0.5mm
Max rolling force: 12000KN
Rolling speed: normally 110m/min, max 240m/min
Work roller: $\Phi 400 \times 1600$
Backup roller: $\Phi 880 \times 1550$
Motors: Main Mill: 750KW×2, Decoiler: 225KW×2, Recoiler: 225KW×2
Material of rollers: 9Cr2Mo

The 4-Hi cold-rolling mills, one of the metal coil cold-rolling mill, that are made from good quality raw material. A four-high cold-rolling mill has four rolls, two small and two large. The two small rolls are work rolls in contact with the metal coil; and the two large rolls are back-up rolls, which contact the back side of the small work rolls.

A2-1.7 Conclusion

The sheet-entrant angle, friction coefficient, thermal contact conductance coefficient could not be measured; there is no available equipment for the measurement. Therefore, the entrance angle can be determined theoretically with the given roll diameter, sheet input thickness and the sheet output thickness.
Figure A3-1: Picture showing Elemental Optical Emission Spectrometry
A3-1 Chemical Analysis of both cold-rolled and hot-rolled aluminium alloy samples (Emission spectrometer)

### QMatrix Analysis Results

**Sample Identification**

<table>
<thead>
<tr>
<th>SampleNo</th>
<th>CR-Al</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Si %**  
1. 0.270  
2. 0.272  
3. 0.284  

**Fe %**  
1. 0.816  
2. 0.795  
3. 0.879  

**Cu %**  
1. 0.085  
2. 0.050  
3. 0.047  

**Mn %**  
1. 0.075  
2. 0.074  
3. 0.074  

**Mg %**  
1. 0.023  
2. 0.024  
3. 0.024  

**Cr %**  
1. 0.013  
2. 0.015  
3. 0.022  

**Ni %**  
1. 0.012  
2. 0.013  
3. 0.023  

**Zn %**  
1. 0.067  
2. 0.070  
3. 0.071  

**Ti %**  
1. 0.022  
2. 0.021  
3. 0.021  

**Ag %**  
1. <0.0010  
2. <0.0010  
3. <0.0010  

**B %**  
1. 0.0046  
2. 0.0046  
3. 0.0053  

**Be %**  
1. <0.0010  
2. <0.0010  
3. <0.0010  

**Ba %**  
1. <0.0020  
2. <0.0020  
3. <0.0020  

**Ca %**  
1. >0.017  
2. >0.017  
3. >0.017  

**Cd %**  
1. 0.0029  
2. 0.0029  
3. 0.0029  

**Co %**  
1. <0.0020  
2. <0.0020  
3. <0.0020  

**Cu %**  
1. 0.0061  
2. 0.0061  
3. 0.0061  

**Ga %**  
1. 0.0021  
2. 0.0021  
3. 0.0021  

**Li %**  
1. <0.0010  
2. <0.0010  
3. <0.0010  

**Na %**  
1. 0.0048  
2. 0.0048  
3. 0.0048  

**Pb %**  
1. 0.00041  
2. 0.00041  
3. 0.00041  

**Sn %**  
1. 0.00023  
2. 0.00023  
3. 0.00023  

**Sr %**  
1. 0.00052  
2. 0.00052  
3. 0.00052  

**V %**  
1. <0.0010  
2. <0.0010  
3. <0.0010  

**Zr %**  
1. 0.00071  
2. 0.00071  
3. 0.00071  

**Al %**  
1. 98.54  
2. 98.54  
3. 98.54  

**Concentrations**

1/1
# QMatrix Analysis Results

## Sample Identification

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Ni</th>
<th>Zn</th>
<th>Ti</th>
<th>Ag</th>
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<tr>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>1.</td>
<td>0.441</td>
<td>1.179</td>
<td>0.150</td>
<td>0.073</td>
<td>0.030</td>
<td>0.0071</td>
<td>0.010</td>
<td>0.067</td>
<td>0.013</td>
<td>&lt;0.00020</td>
</tr>
<tr>
<td>2.</td>
<td>0.512</td>
<td>1.437</td>
<td>0.122</td>
<td>0.074</td>
<td>0.042</td>
<td>0.0062</td>
<td>0.012</td>
<td>0.076</td>
<td>0.0096</td>
<td>&lt;0.00020</td>
</tr>
<tr>
<td>3.</td>
<td>0.482</td>
<td>1.398</td>
<td>0.165</td>
<td>0.075</td>
<td>0.032</td>
<td>0.0069</td>
<td>0.013</td>
<td>0.073</td>
<td>0.010</td>
<td>&lt;0.00020</td>
</tr>
</tbody>
</table>

| 0.478 | 1.338 | 0.146 | 0.074 | 0.035 | 0.0067 | 0.012 | 0.072 | 0.011 | <0.00020 |

| B | Ba | Be | Bi | Ca | Cd | Co | Ga | In | Li |
| % | %  | %  | %  | %  | %  | %  | %  | %  | %  |
| 1. | 0.0057 | 0.00044 | 0.00084 | <0.0030 | >0.0048 | 0.00077 | <0.0010 | 0.017 | <0.0040 | <0.00050 |
| 2. | 0.0074 | <0.00010 | 0.0012 | <0.0036 | >0.0048 | 0.00077 | <0.0010 | 0.016 | <0.0040 | <0.00050 |
| 3. | 0.0069 | <0.00010 | 0.0010 | 0.0033 | >0.0048 | <0.00050 | <0.0010 | 0.018 | <0.0040 | <0.00050 |

| 0.0067 | 0.00021 | 0.0010 | 0.0031 | ~0.0048 | 0.00068 | <0.0010 | 0.017 | <0.0040 | <0.00050 |

| Na | P | Pb | Sn | V | Zr | Al |
| %  | %  | %  | %  | %  | %  | %  |
| 1. | 0.0022 | <0.0010 | 0.0072 | <0.0015 | 0.0048 | <0.0020 | 97.97 |
| 2. | 0.0037 | <0.0010 | 0.0058 | <0.0015 | 0.0031 | <0.0020 | 97.65 |
| 3. | 0.0030 | <0.0010 | 0.012 | 0.0023 | 0.0045 | 0.00037 | 97.68 |

| 0.0030 | <0.0010 | 0.0083 | 0.0018 | 0.0041 | 0.00026 | 97.77 |

| 0.00075 | 0.0033 | 0.00046 | 0.00091 | 0.00010 | 0.177 |
| 25.00 | 39.76 | 25.56 | 22.20 | 38.46 | 0.181 |

All110

Bruker Elemental

Concentrations

1/1
Figure A3-2: Picture of Instron Model 4400 Universal Testing System used in the experimental study

Figure A3-3: Picture of Vickers Micro-Hardness Tester used in the experimental study
Figure A3-4: Picture of an automated Mecatome T300 cutting machine

Figure A3-5: Picture of an automated CitoPress -10/20/Ø30 mm mounting machine
Figure A3-6: Picture of an automated grinding/polishing machine

Figure A3-7: Picture of some of the mounted, grinded, polished and etched samples
Figure A3-8: Picture of Olympus BX51M Light Optical Microscopy equipped with an Olympus DP25 digital camera

Figure A3-9: Picture of TESCAN VEGA Scanning Electron Microscope (SEM) equipped with Oxford Energy Dispersion Spectrometry (EDS)
A3-2 Detailed drawings of the tensile specimen samples for the tensile test

Note: 1. Machining to be ±0.25 mm unless otherwise stated. 2. Remove all sharp edges and burrs.
Note:
1. Machining to be ±0.25 mm unless otherwise stated
2. Remove all sharp edges and burrs
A3-3 Grain size measurement results for both hot-rolled, reversing cold-rolled and non-reversing cold-rolled samples

Optical micrographs of hot-rolled AA8015 sample (7 mm thickness) showing magnified grain size measurement: (a) grain structure (longitudinal section) of hot-rolled AA8015-alloy (b) grain structure (transverse section) of hot-rolled AA8015-alloy

Optical micrographs of reversing cold-rolled AA8015 sample (1.2 mm thickness) showing magnified grain size measurement: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy
Optical micrographs of non-reversing cold-rolled AA8015 sample (6 mm thickness) showing magnified grain size measurement: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy

Optical micrographs of non-reversing cold-rolled AA8015 sample (5 mm thickness) showing magnified grain size measurement: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy
Optical micrographs of non-reversing cold rolled AA8015 sample (4 mm thickness) showing magnified grain size measurement: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy

Optical micrographs of non-reversing cold rolled AA8015 sample (3 mm thickness) showing magnified grain size measurement: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy
Optical micrographs of non-reversing cold rolled AA8015 sample (2 mm thickness) showing magnified grain size measurement: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy

Optical micrographs of non-reversing cold rolled AA8015 sample (1 mm thickness) showing magnified grain size measurement: (a) grain structure (longitudinal section) of cold-rolled AA8015-alloy (b) grain structure (transverse section) of cold-rolled AA8015-alloy
A3-4 Surface roughness test results

Surface roughness test result for hot rolled AA8015 with 7 mm thickness

Surface roughness test result for cold-rolled AA8015 with 1.2 mm thickness
Surface roughness test result for hot rolled AA8015 sample grinded with 320 grit SiC paper

<table>
<thead>
<tr>
<th>Measuring conditions</th>
<th>TKU600</th>
<th>TKU600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe:</td>
<td>160 µm</td>
<td>160 µm</td>
</tr>
<tr>
<td>Linear traverse unit:</td>
<td>waveline 60</td>
<td>waveline 60</td>
</tr>
<tr>
<td>Traverse length [L]:</td>
<td>4.80 mm</td>
<td>4.80 mm</td>
</tr>
<tr>
<td>Speed [V]:</td>
<td>0.15 mm/s</td>
<td>0.15 mm/s</td>
</tr>
<tr>
<td>Filter for profile P-R-W:</td>
<td>ISO 11562</td>
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<tr>
<td>Lc / Ls:</td>
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<td>OFF</td>
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</tbody>
</table>

Statistics n=1

No. Parameters Xq Range S Xmax Xmin
1. Ra 0.65 µm
2. Rz 5.57 µm
3. Rmax 6.37 µm
4. Rz

Surface roughness test result for hot-rolled AA8015 sample grinded with 800 grit SiC paper

<table>
<thead>
<tr>
<th>Measuring conditions</th>
<th>TKU600</th>
<th>TKU600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe:</td>
<td>160 µm</td>
<td>160 µm</td>
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<tr>
<td>Linear traverse unit:</td>
<td>waveline 60</td>
<td>waveline 60</td>
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<tr>
<td>Traverse length [L]:</td>
<td>4.80 mm</td>
<td>4.80 mm</td>
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<tr>
<td>Speed [V]:</td>
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<tr>
<td>Lc / Ls:</td>
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<td>OFF</td>
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</tbody>
</table>

Statistics n=1

No. Parameters Xq Range S Xmax Xmin
1. Ra 1.37 µm
2. Rz 7.79 µm
3. Rmax 6.45 µm
4. Rz
Surface roughness test result for hot-rolled AA8015 sample ground with 1200 grit SiC paper.

Surface roughness test result for hot-rolled AA8015 sample diamond polished with MD-Mol.
Surface roughness test result for cold-rolled AA8015 sample grinded with 320 grit SiC paper

Surface roughness test result for cold-rolled AA8015 sample grinded with 800 grit SiC paper
Surface roughness test result for cold-rolled AA8015 sample ground with 1200 grit SiC paper:

- **Ra**: 0.18 µm
- **Rz**: 1.26 µm
- **Rmax**: 1.51 µm

Surface roughness test result for cold-rolled AA8015 sample diamond polished with MD-Mol:

- **Ra**: 0.04 µm
- **Rz**: 0.40 µm
- **Rmax**: 0.54 µm

---

**Surface roughness test result for cold-rolled AA8015 sample ground with 1200 grit SiC paper**

**Surface roughness test result for cold-rolled AA8015 sample diamond polished with MD-Mol**

---
APPENDIX B

B1: The slope and tafel analysis resulting from electrochemical corrosion testing

B1-1 Hot-rolled AA8015-alloy samples at different surface roughness

B1-1.1 Surface roughness, $R_a = 1.37$ µm

Sample 1

<table>
<thead>
<tr>
<th>Slope analysis</th>
<th>Tafel analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{a1} = -0.720$ V</td>
<td>$E_{a1} = -0.827$ V; $E_{a2} = -0.801$ V</td>
</tr>
<tr>
<td>$E_{c1} = -0.704$ V</td>
<td>$E_{c1} = -0.657$ V; $E_{c2} = -0.645$ V</td>
</tr>
</tbody>
</table>
Sample 2

Slope analysis

$E_{a1} = -0.701 \text{ V}$

$E_{c1} = -0.657 \text{ V}$

Tafel analysis

$E_{a1} = -0.831 \text{ V;}$ $E_{a2} = -0.802 \text{ V}$

$E_{c1} = -0.657 \text{ V;}$ $E_{c2} = -0.649 \text{ V}$

![Slope analysis graph](image1)

![Tafel analysis graph](image2)
Sample 3

Slope analysis

\[ E_{a1} = -0.704 \text{ V} \]
\[ E_{c2} = -0.688 \text{ V} \]

Tafel analysis

\[ E_{a1} = -0.844 \text{ V}; \quad E_{a2} = -0.810 \text{ V} \]
\[ E_{c1} = -0.660 \text{ V}; \quad E_{c2} = -0.649 \text{ V} \]
B1-1.2 Surface roughness, $R_a = 0.65 \, \mu m$

Sample 1

**Slope analysis**
- $E_{a1} = -0.728 \, V$
- $E_{c2} = -0.712 \, V$

**Tafel analysis**
- $E_{a1} = -0.837 \, V$; $E_{a2} = -0.811 \, V$
- $E_{c1} = -0.661 \, V$; $E_{c2} = -0.651 \, V$
Sample 2

Slope analysis

\[ E_{a1} = -0.730 \text{ V} \]
\[ E_{c2} = -0.714 \text{ V} \]

Tafel analysis

\[ E_{a1} = -0.862 \text{ V} \]
\[ E_{a2} = -0.838 \text{ V} \]
\[ E_{c1} = -0.664 \text{ V} \]
\[ E_{c2} = -0.654 \text{ V} \]
Sample 3

Slope analysis

\[ E_{a1} = -0.697 \text{ V} \]
\[ E_{c2} = -0.681 \text{ V} \]

Tafel analysis

\[ E_{a1} = -0.826 \text{ V}; \quad E_{a2} = -0.796 \text{ V} \]
\[ E_{c1} = -0.662 \text{ V}; \quad E_{c2} = -0.653 \text{ V} \]
B1-1.3 Surface roughness, $R_a = 0.19 \, \mu m$

Sample 1

Slope analysis (Pol. Res.)

- $E_{a1} = -0.708 \, V$
- $E_{c2} = -0.692 \, V$

Tafel analysis

- $E_{a1} = -0.861 \, V$; $E_{a2} = -0.813 \, V$
- $E_{c1} = -0.660 \, V$; $E_{c2} = -0.582 \, V$
Sample 2

Slope analysis (Pol. Res.)

$E_{a1} = -0.686 \text{ V}$
$E_{c2} = -0.670 \text{ V}$

Tafel analysis

$E_{a1} = -0.831 \text{ V}$; $E_{a2} = -0.797 \text{ V}$
$E_{c1} = -0.621 \text{ V}$; $E_{c2} = -0.598 \text{ V}$
Sample 3

Slope analysis (Pol. Res.)

\[ E_{a1} = -0.694 \text{ V} \]
\[ E_{c2} = -0.678 \text{ V} \]

Tafel analysis

\[ E_{a1} = -0.850 \text{ V} \]
\[ E_{a2} = -0.817 \text{ V} \]
\[ E_{c1} = -0.627 \text{ V} \]
\[ E_{c2} = -0.603 \text{ V} \]

B1-1.4 Surface roughness, \( R_a = 0.10 \mu\text{m} \)
Sample 1

Slope analysis

\[ E_{a1} = -0.710 \text{ V} \]
\[ E_{c2} = -0.694 \text{ V} \]

Tafel analysis

\[ E_{a1} = -0.863 \text{ V}; \quad E_{a2} = -0.799 \text{ V} \]
\[ E_{c1} = -0.618 \text{ V}; \quad E_{c2} = -0.590 \text{ V} \]
Slope analysis

$E_{al} = -0.733 \text{ V}$

$E_{c2} = -0.717 \text{ V}$

Tafel analysis

$E_{al} = -0.862 \text{ V}$; $E_{a2} = -0.836 \text{ V}$

$E_{cl} = -0.570 \text{ V}$; $E_{c2} = -0.544 \text{ V}$

Sample 3

Slope analysis

Tafel analysis
\[ E_{a1} = -0.735 \text{ V} \quad E_{a2} = -0.875 \text{ V} \quad E_{a2} = -0.848 \text{ V} \]
\[ E_{c1} = -0.591 \text{ V} \quad E_{c2} = -0.572 \text{ V} \]

B1-2 Cold-rolled AA8015-alloy samples at different surface roughness

B1-2.1 Surface roughness, \( R_a = 1.54 \text{ µm} \)

Sample 1
Slope analysis

\( E_{a1} = -0.745 \text{ V} \)
\( E_{c1} = -0.729 \text{ V} \)

Tafel analysis

\( E_{a1} = -0.948 \text{ V}; \quad E_{a2} = -0.838 \text{ V} \)
\( E_{c1} = -0.667 \text{ V}; \quad E_{c2} = -0.651 \text{ V} \)
$E_{a1} = -0.729\, \text{V}$ \quad $E_{a1} = -0.863\, \text{V}$ \quad $E_{a2} = -0.835\, \text{V}$

$E_{c2} = -0.713\, \text{V}$ \quad $E_{c1} = -0.679\, \text{V}$ \quad $E_{c2} = -0.664\, \text{V}$

Slope analysis

Tafel analysis

Sample 3

Slope analysis \quad Tafel analysis
\[ E_{a1} = -0.731 \text{ V} \quad E_{a1} = -0.922 \text{ V} \quad E_{a2} = -0.832 \text{ V} \]
\[ E_{c2} = -0.716 \text{ V} \quad E_{c1} = -0.686 \text{ V} \quad E_{c2} = -0.675 \text{ V} \]

**Slope analysis**

**Tafel analysis**

B1-2.2 Surface roughness, \( R_a = 0.83 \mu m \)

Sample 1
Slope analysis

$E_{a1} = -0.752$ V

$E_{a2} = -0.736$ V

Tafel analysis

$E_{a1} = -0.889$ V; $E_{a2} = -0.857$ V

$E_{c1} = -0.680$ V; $E_{c2} = -0.671$ V

Sample 2

Slope analysis

$E_{a1} = -0.744$ V

Tafel analysis

$E_{a1} = -0.845$ V; $E_{a2} = -0.810$ V
$E_{c2} = -0.728 \text{ V}$  

$E_{c1} = -0.670 \text{ V};$  

$E_{c2} = -0.663 \text{ V}$

**Slope analysis**

**Tafel analysis**

Sample 3

<table>
<thead>
<tr>
<th>Slope analysis</th>
<th>Tafel analysis</th>
</tr>
</thead>
</table>
| $E_{a1} = -0.783 \text{ V}$ | $E_{a1} = -0.903 \text{ V};$  
| $E_{c2} = -0.767 \text{ V}$ | $E_{c1} = -0.676 \text{ V};$  
|                           | $E_{c2} = -0.663 \text{ V}$ |
B1-2.3 Surface roughness, $R_a = 0.18 \mu m$

Sample 1

Slope analysis

$E_{a1} = -0.687 \text{ V}$

Tafel analysis

$E_{a1} = -0.861 \text{ V}; \quad E_{a2} = -0.804 \text{ V}$
$E_{c2} = -0.671 \text{ V}$  \hspace{1cm} $E_{cl} = -0.601 \text{ V}$;  \hspace{1cm} $E_{c2} = -0.582 \text{ V}$

Slope analysis

$E_{a1} = -0.695 \text{ V}$  \hspace{1cm} $E_{a1} = -0.842 \text{ V}$;  \hspace{1cm} $E_{a2} = -0.823 \text{ V}$

$E_{c2} = -0.679 \text{ V}$  \hspace{1cm} $E_{cl} = -0.650 \text{ V}$;  \hspace{1cm} $E_{c2} = -0.633 \text{ V}$

Sample 2

Tafel analysis
Sample 3

Slope analysis

\[ E_{a1} = -0.703 \text{ V} \]
\[ E_{c1} = -0.687 \text{ V} \]

Tafel analysis

\[ E_{a1} = -0.865 \text{ V} ; \quad E_{a2} = -0.806 \text{ V} \]
\[ E_{c1} = -0.620 \text{ V} ; \quad E_{c2} = -0.605 \text{ V} \]
B1-2.4 Surface roughness, $R_a = 0.04 \, \mu m$

**Sample 1**

Slope analysis (Pol. Res.) Tafel analysis

$E_{a1} = -0.676 \, V$ $E_{a1} = -0.851 \, V$; $E_{a2} = -0.787 \, V$

$E_{c2} = -0.660 \, V$ $E_{c1} = -0.615 \, V$; $E_{c2} = -0.603 \, V$
Sample 2

Slope analysis

$E_{a1} = -0.715 \text{ V}$

$E_{c1} = -0.621 \text{ V}$

Tafel analysis

$E_{a1} = -0.840 \text{ V}$; $E_{a2} = -0.786 \text{ V}$

$E_{c1} = -0.581 \text{ V}$
Sample 3

Slope analysis

- $E_{a1} = -0.717 \text{ V}$
- $E_{c1} = -0.701 \text{ V}$

Tafel analysis

- $E_{a1} = -0.887 \text{ V}$
- $E_{a2} = -0.849 \text{ V}$
- $E_{c1} = -0.614 \text{ V}$
- $E_{c2} = -0.583 \text{ V}$
Slope analysis

Tafel analysis