

MICROSTRUCTURE, MECHANICAL PROPERTIES AND CORROSION
BEHAVIOR OF AA5083 ALUMINUM ALLOY MODIFIED WITH
RARE EARTH ELEMENTS

ABDELAISALAM ALI AL-BAKOOSH

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

School of Mechanical Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

SEPTEMBER 2020

DEDICATION

**To my loved mother and the spirit of my loved father, may 'ALLAH' give him
a pleasant place in Paradise**

“My Success Is Yours Too”

ACKNOWLEDGEMENT

Principally, I gave thanks and praises to ALLAH (SWT) for his compassion, mercy, providence, liveliness, sound health, and will power for me throughout

I would like to thank and appreciate the Libyan Ministry of Higher Education (LMHE) for providing financial support, despite the difficult circumstances in which my beloved country is passing

I would like to express my sincere gratitude and appreciation to my supervisor, Professor. Dr. Mohd Hasbullah B Hj. Idris for his guidance and infinite patience. I am always grateful to have benefited from his vast wealth of knowledge, experience, simplicity, humility, friendliness, and accessibility. Without his valuable advice, encouragement, I would not have completed this thesis. He has been continuously supportive and encouraging during the period of the study.

I would like to thank Professor. Dr. Jamaliah Idris for her useful advice and encouragement. Without her valuable advice, kind encouragement, I would not have reached this point.

I wish to express my gratitude and thanks to all people who help me by a direct or indirect way during my study.

This Ph.D. degree will never be accomplished without the prayers of my mother, who pray to me every day. She was the only one who could truly cheer me up during difficult times of my research.

ABSTRACT

The commercial AA5083 alloy is a non-heat-treatable alloy with high strength-to-weight ratio. It has good welding properties, ease of machinability and formability, and satisfactory corrosion property resistance in marine and industrial environments. Despite the advantages it possesses, the AA5083 alloy has some limitations such as its moderate strength, and susceptibility to localised corrosion (LC) in the marine environment that increases under high-speed conditions. It is also susceptible to intergranular corrosion (IGC) and intergranular stress corrosion cracking (IGSCC) at the temperature range of 50°C to 200°C. Previous studies showed that the addition of an appropriate amount of rare earth elements (REEs) can improve the microstructure, mechanical properties, and corrosion resistance of Al-alloys. This research was aimed at investigating the effects of REEs (Ce, Pr, and Ce + Pr) additions on the microstructure, mechanical properties, and corrosion behavior of the AA5083 alloy. Ce and Pr were added to AA5083 alloy using in-situ casting process in the amount of 0.1 wt% to 1.0 wt% whilst the combination of Ce-Pr was between 0.1 wt% and 0.5 wt%. Non-destructive testing (NDT) was conducted to assess the quality of the samples produced whilst the homogenisation process was performed at 450°C for 24 hr to achieve homogeneous microstructure. Characterisation of the modified AA5083 alloys was conducted using optical microscope (OM), variable pressure scanning electron microscope (VPSEM) equipped with energy dispersive spectrometer (EDS) and x-ray diffraction (XRD). Corrosion behavior was investigated by visual assessment (ASSET-Test), IGC susceptibility by nitric acid mass loss test (NAMLT), electrochemical behaviour testing in 3.5% NaCl solution by Tafel extrapolation (TE) and potentiodynamic polarization (PDP), and full immersion corrosion tests in 3.5% NaCl solution under static and high-speed conditions at room temperature. Tensile properties and impact tests were also conducted to determine mechanical properties of the alloy. In addition, erosion prediction test was performed by impingement of solid spherical particle at normal incidence. The findings indicated that addition of Ce, Pr, and Ce + Pr to the AA5083 alloy resulted in the reduction of grain size. The average grain size were reduced from 105 μm to 72 μm and 107 μm to 74 μm respectively, as addition of Ce and Pr from 0.1 to 1.0 wt%. Addition of Ce-Pr combination in the amount of 0.1% to 0.5% resulted in average grain size reduction from 98 μm to 65 μm. The presence of stable precipitate (REE-rich) phases played a critical role in the grain refinement, thereby improving the mechanical properties. The stable phases reduced the β-phase (Al₃Mg₂) and Fe-rich and Mg-rich phases, which are a major cause of LC, IGC, and IGSCC, thus improving the corrosion resistance. These properties were more prominent in the case of addition of Ce + Pr combined than in individual addition of Ce or Pr. The modified AA5083 alloy with 0.5% Ce + 0.5% Pr addition had the best overall improvement in terms of mechanical properties and corrosion behaviour compared to other modified AA5083 alloys. The average grain size was reduced by 39.8%. Toughness, yield strength, and ultimate strength improved by 21%, 27.5% and, 53.3 % respectively whilst corrosion rate decreased by 31.2%. Thus, it is suggested that, REEs can be promising candidates for the alloying elements of AA5083.

ABSTRAK

Aloi AA5083 komersial merupakan aloi tidak-boleh-rawat haba dengan sifat nisbah kekuatan-berat yang tinggi. Ia mempunyai sifat kimpalan yang baik, mudah dimesin dan dibentuk, dan ketahanan kakisan yang memuaskan dalam persekitaran marin dan industri. Walaupun mempunyai kelebihan, aloi tersebut mempunyai beberapa kelemahan seperti kekuatan yang sederhana, kerentanan terhadap kakisan setempat (LC) dalam persekitaran marin yang meningkat dalam keadaan kelajuan tinggi. Ia juga rentan terhadap kakisan antara butir (IGC) dan kakisan tegasan retak antara butir (IGSCC) pada julat suhu dari 50°C hingga 200°C. Kajian sebelum ini menunjukkan penambahan unsur nadir bumi (REEs) dengan jumlah yang sesuai boleh menambahbaik struktur mikro, sifat mekanik dan ketahanan kakisan aloi Al. Penyelidikan ini dilaksanakan bertujuan untuk mengkaji kesan mencampurkan REE (Ce, Pr, dan Ce + Pr) terhadap struktur mikro, sifat mekanik dan kelakuan kakisan aloi AA5083. Ce dan Pr dicampur pada aloi AA5083 dengan menggunakan proses penuangan in-situ dalam julat dari 0.1 hingga 1.0% berat manakala campuran kombinasi Ce-Pr adalah antara 0.1% berat hingga 1% berat. Ujian Tanpa Musnah (NDT) dilakukan untuk menilai kualiti sampel yang dihasilkan manakala proses penghomogenan dilakukan pada suhu 450°C selama 24 jam untuk mendapatkan struktur mikro yang homogen. Pencirian aloi AA5083 yang diubahsuai dilaksanakan dengan menggunakan mikroskop optik (OM), mikroskop imbasan elektron tekanan berubah-ubah (VPSEM) yang dilengkapi dengan spektrometer serakan tenaga (EDS) dan pembelauan sinar-x, (XRD). Kelakuan kakisan dikaji melalui penilaian visual pengelupasan dan ujian kerentanan kakisan lekuk (ASSET), kerentanan IGC dengan ujian kehilangan jisim asid nitrik (NAMLT), ujian kelakuan elektrokimia dalam larutan NaCl 3.5% oleh penetuluran Tafel (TE) dan polarisasi potensiodinamik (PDP), dan ujian kakisan rendaman penuh dalam larutan 3.5% NaCl dalam keadaan statik dan kelajuan tinggi pada suhu bilik. Sifat tegangan, dan ujian hentaman juga dilaksanakan bagi menentukan sifat mekanikal aloi tersebut. Selain itu, ujian ramalan hakisan dilaksanakan dengan menghentam partikel pepejal sfera pada sudut normal. Hasil kajian menunjukkan, mencampurkan Ce, Pr, dan Ce + Pr pada aloi AA5083 mengurangkan saiz butiran. Saiz butiran berkurang dari 105µm ke 72 µm dan 107 µm ke 74 µm masing-masing bilamana Ce dan Pr ditambah dari 0.1 ke 1.0% berat. Penambahan kombinasi Ce + Pr dalam jumlah 0.1 to 0.5% berat menghasilkan pengurangan saiz butiran purata dari 98µm ke 65µm. Kewujudan fasa endapan stabil (REE diperkaya) memainkan peranan penting dalam penghalusan butiran, dengan itu menambahbaik sifat mekanik. Fasa stabil tersebut mengurangkan fasa-β (Al₃Mg₂) dan fasa Fe dan Mg diperkaya, yang merupakan penyebab utama LC, IGC dan IGSCC, dengan itu menambahbaik rintangan kakisan. Sifat-sifat ini lebih terserlah bagi kombinasi Ce + Pr berbanding campuran secara individu Ce atau Pr. Aloi AA5083 yang diubahsuai dengan campuran 0.5% Ce + 0.5% Pr menghasilkan penambahbaikan keseluruhan yang terbaik dari segi sifat mekanik dan kelakuan kakisan berbanding dengan aloi AA5083 lain yang diubahsuai. Saiz butiran purata berkurang sebanyak 39.8%. Keliatan, kekuatan alah dan tegangan utama ditambahbaik masing-masing sebanyak 21%, 27.5% dan 53.3% manakala kadar kakisan berkurang sebanyak 31.2%. Dengan itu, REEs boleh dicadangkan sebagai calon yang sesuai sebagai unsur paduan bagi AA5083.

TABLE OF CONTENTS

| | TITLE | PAGE |
|------------------|--|--------------|
| | DECLARATION | iii |
| | DEDICATION | iv |
| | ACKNOWLEDGEMENT | v |
| | ABSTRACT | vi |
| | ABSTRAK | vii |
| | TABLE OF CONTENTS | viii |
| | LIST OF TABLES | xix |
| | LIST OF FIGURES | xxi |
| | LIST OF ABBREVIATIONS | xxxii |
| | LIST OF APPENDICES | xxxiv |
| CHAPTER 1 | INTRODUCTION | 1 |
| | 1.1 Background of the study | 1 |
| | 1.2 Problem Statement | 3 |
| | 1.3 Research objectives | 4 |
| | 1.4 Scope of the research | 4 |
| | 1.5 Significance of the research | 5 |
| | 1.6 Thesis organization | 6 |
| CHAPTER 2 | LITERATURE REVIEW | 7 |
| | 2.1 Introduction | 7 |
| | 2.1.1 The aluminium alloys | 7 |
| | 2.1.2 The 5xxx series of aluminium-magnesium alloys | 9 |
| | 2.1.3 The AA5083 aluminum-magnesium-manganese Alloy | 11 |
| | 2.1.4 Aluminium-Magnesium-Manganese ternary system (Al-Mg-Mn ternary system) | 14 |
| | 2.2 The Rare Earth Elements | 15 |
| | 2.2.1 Introduction | 15 |
| | 2.2.2 Classification of REEs | 16 |

| | | |
|---------|---|----|
| 2.2.3 | The common properties of REEs | 17 |
| 2.2.4 | Crystal structure of rare earth elements. | 18 |
| 2.2.5 | The rare earth elements (REEs) applications | 20 |
| 2.2.6 | Precautions for safe handling of REEs | 21 |
| 2.3 | Casting of Al-alloys | 21 |
| 2.3.1 | Introduction | 21 |
| 2.3.2 | Casting classification of Al-alloys | 21 |
| 2.3.3 | Classifications of defects in Al-alloys die cast products | 22 |
| 2.3.4 | Degassing of Aluminum alloys | 24 |
| 2.3.5 | Inspection and quality control of casting | 25 |
| 2.4 | Alloying elements | 26 |
| 2.4.1 | Introduction | 26 |
| 2.4.2 | Effect of alloying elements on the functionality of Al-Mg Alloys | 28 |
| 2.4.3 | Effects of REEs addition on the functionality of Al-Mg Alloys | 30 |
| 2.5 | Material characterization methods | 35 |
| 2.6 | Homogenization process of Al-alloys | 35 |
| 2.6.1 | Introduction | 35 |
| 2.6.2 | Effect of the homogenization process on the characterization of AA5xxx alloys | 37 |
| 2.7 | The microstructure of aluminum alloys | 39 |
| 2.7.1 | Grain refinement of Al-alloys | 39 |
| 2.7.1.1 | Effect of REEs additions on grain-refining performance of Al-alloys | 41 |
| 2.7.2 | The intermetallic compounds (IMCs) | 42 |
| 2.7.2.1 | Introduction | 42 |
| 2.7.2.2 | The intermetallic compounds in 5xxx Series Al-alloys | 42 |
| 2.7.2.3 | Intermetallic compounds IMCs in AA5083 alloy | 44 |
| 2.7.3 | Phase and microstructure of Al with rare earth elements REEs | 46 |
| 2.7.3.1 | Aluminum-Praseodymium binary system (the Al-Pr system) | 47 |

| | | |
|-----|---|----|
| | 2.7.3.2 Aluminum-Magnesium-Praseodymium ternary system (The Al-Mg-Pr system) | 48 |
| | 2.7.3.3 Aluminum-Cerium binary system (The Al-Ce system) | 48 |
| | 2.7.3.4 Aluminum-Magnesium-Cerium ternary system (the Al-Mg-Ce system) | 49 |
| 2.8 | Corrosion of Al-alloys | 50 |
| | 2.8.1 Fundamentals of corrosion | 50 |
| | 2.8.2 General corrosion | 52 |
| | 2.8.3 Pitting Corrosion | 52 |
| | 2.8.4 Exfoliation Corrosion (EFC) | 55 |
| | 2.8.5 The intergranular corrosion (IGC) | 58 |
| | 2.8.6 Corrosion-erosion | 62 |
| | 2.8.7 Aqueous Corrosion of Al-alloys | 64 |
| | 2.8.7.1 Aqueous corrosion of AA5083 alloy in NaCl Solution | 66 |
| | 2.8.8 Electrochemical corrosion testing | 67 |
| | 2.8.8.1 Introduction | 67 |
| | 2.8.8.2 Potentiodynamic polarization test | 68 |
| | 2.8.8.3 Tafel extrapolation (TE) | 68 |
| | 2.8.8.4 Calculation of corrosion rates using quantitative electrochemical data | 69 |
| | 2.8.8.5 Electrochemical corrosion of AA5083 alloy in NaCl solution | 70 |
| | 2.8.8.6 Impact of the addition of alloying elements on electrochemical corrosion of the AA5083 alloys | 71 |
| | 2.8.8.7 Effect of additions of REEs on corrosion of AA5083 alloys | 72 |
| | 2.8.9 Erosion | 73 |
| | 2.8.9.1 Introduction | 73 |
| | 2.8.9.2 Erosion by single solid particle impingement. | 73 |
| | 2.8.9.3 Physical phenomena for impingement of a single spherical rigid particle | 74 |
| | 2.8.9.4 Erosion mechanisms of solid particle impact | 76 |

| | | |
|------------------|--|-----------|
| 2.9 | Mechanical properties | 78 |
| 2.9.1 | Mechanical testing techniques | 78 |
| 2.9.2 | Mechanical properties of Al-Mg alloys | 79 |
| 2.9.3 | Strengthening mechanisms in Al-alloys | 79 |
| 2.9.3.1 | Strengthening by strain hardening | 80 |
| 2.9.3.2 | Strengthening by precipitation hardening and dispersion strengthening | 80 |
| 2.9.3.3 | Strengthening by solid-solution | 81 |
| 2.9.3.4 | Strengthening by Grain Size Reduction | 81 |
| 2.9.4 | Fundamentals of tensile testing | 82 |
| 2.9.4.1 | Impact of the addition of REEs on the strength of Al-Mg alloys | 83 |
| 2.9.5 | Fundamentals of Impact testing | 83 |
| 2.10 | Summary | 86 |
| CHAPTER 3 | RESEARCH METHODOLOGY | 87 |
| 3.1 | Introduction | 87 |
| 3.1.1 | Experimental approach | 87 |
| 3.2 | Materials | 88 |
| 3.3 | Casting process of AA5083 alloys | 90 |
| 3.3.1 | Casting process of the modified AA5083 alloys | 90 |
| 3.4 | Non-destructive testing NDT technique | 95 |
| 3.4.1 | Visual inspection test (VT) | 95 |
| 3.4.2 | Liquid penetrant test (LT) | 95 |
| 3.4.3 | Ultrasonic test (UT) | 96 |
| 3.5 | Chemical analysis | 96 |
| 3.6 | Homogenization process | 97 |
| 3.7 | Materials characterization of AA5083 alloys | 99 |
| 3.7.1 | Introduction | 99 |
| 3.7.1.1 | Optical microscopy (OM) | 99 |
| 3.7.1.2 | VPSEM/EDS | 100 |
| 3.7.1.3 | X-ray diffractometry (XRD) | 100 |
| 3.7.2 | Metallographic sample preparation technique | 101 |
| 3.7.3 | Determining average grain size | 102 |

| | | | |
|------------------|-------|---|------------|
| | 3.7.4 | Identification and characterization of intermetallic compounds (IMCs) | 103 |
| 3.8 | | Corrosion tests | 103 |
| | 3.8.1 | Electrochemical corrosion testing | 103 |
| | 3.8.2 | Full immersion corrosion tests | 105 |
| | 3.8.3 | Immersion corrosion tests under high-speed conditions. | 108 |
| | 3.8.4 | Nitric acid mass loss test (NAMLT) procedure | 110 |
| | 3.8.5 | Exfoliation and pitting corrosion susceptibility (ASSET-Test) | 112 |
| | 3.8.6 | Prediction tests of impingement erosion using single particles | 114 |
| 3.9 | | Mechanical tests | 117 |
| | 3.9.1 | Uniaxial tensile tests | 117 |
| | 3.9.2 | Charpy v-notch impact testing | 120 |
| CHAPTER 4 | | RESULTS AND DISCUSSION | 123 |
| 4.1 | | Casting process | 123 |
| | 4.1.1 | Quality assessment of the cast AA5083 synthetic alloy through NDT | 128 |
| | | 4.1.1.1 Visual inspection (VI) | 128 |
| | | 4.1.1.2 Dye liquid penetrant testing (LT) | 128 |
| | | 4.1.1.3 Ultrasonic testing (UT) | 129 |
| 4.2 | | Homogenization process of AA5083 alloy | 133 |
| | 4.2.1 | Introduction | 133 |
| | 4.2.2 | Evaluation of the homogenization processes for AA5083 alloys | 135 |
| | | 4.2.2.1 Qualitative evaluation of intermetallic compounds of AA5083 alloys | 135 |
| | | 4.2.2.2 Quantitative evaluation of intermetallic compounds of AA5083 alloys | 139 |
| | 4.2.3 | Hardness characterization | 142 |
| | 4.2.4 | X-ray diffraction analysis (XRD) | 144 |
| 4.3 | | Effect of Rare Earth Elements REEs (REEs = Ce, Pr, and Ce + Pr) additions on grain refinement of the AA5083 alloy | 146 |

| | | |
|---------|--|-----|
| 4.3.1 | Effect of Cerium (Ce) additions on grain refinement of AA5083alloy | 146 |
| 4.3.2 | Effect of praseodymium (Pr) addition on grain refinement of AA5083 alloy | 147 |
| 4.3.3 | Effect of (Ce+Pr) additions on grain refinement of the AA5083alloy | 149 |
| 4.4 | Characterization of IMCs for AA5083 alloy and the modified AA5083 alloys with REEs additions | 151 |
| 4.4.1 | Introduction | 151 |
| 4.4.2 | The qualitative evaluation for IMCs | 152 |
| 4.4.2.1 | Characterization of IMCs using the VPSEM / EDS technique | 152 |
| 4.4.2.2 | Morphological characterization of IMCs that exists in AA 5083 alloys and modified alloys AA 5083 with REEs additions | 161 |
| 4.4.2.3 | Characterization of IMCs using XRD Technique | 162 |
| 4.4.3 | The quantitative evaluation for intermetallic compounds IMCs | 168 |
| 4.5 | ASSET-Test for AA5083 alloy and modified AA5083 alloys with REEs additions | 173 |
| 4.5.1 | Introduction | 173 |
| 4.5.2 | Investigation of the control specimen | 174 |
| 4.5.3 | Qualitative assessment for the effect of REEs (Ce, Pr, Ce+Pr) additions on pitting and exfoliation corrosion susceptibility of the AA5083 alloy | 175 |
| 4.5.4 | Quantitative assessment for the effect of REEs (Ce, Pr, Ce+Pr) additions on pitting and exfoliation corrosion susceptibility of the AA5083 alloy | 179 |
| 4.5.5 | Characterization of the samples after ASSET testing via SEM/EDS analysis | 182 |
| 4.6 | Intergranular corrosion (IGC) for AA5083 alloy and modified AA5083 alloys with REEs additions. | 189 |
| 4.6.1 | Introduction | 189 |
| 4.6.2 | Quantitative evaluation of the IGC susceptibility of modified AA5083 alloys with REEs (Ce, Pr, and Ce+Pr) additions | 190 |

| | | |
|---------|---|-----|
| 4.6.2.1 | Effect of Pr additions on the IGC susceptibility of the AA5083 alloy | 191 |
| 4.6.2.2 | Effect of Ce additions on the IGC susceptibility of the AA5083 alloy | 192 |
| 4.6.2.3 | Effect of Ce+Pr additions on the IGC susceptibility of the AA5083 alloy | 194 |
| 4.6.3 | Qualitative evaluation of the IGC susceptibility of the AA5083 alloy and the modified AA5083 alloys | 195 |
| 4.7 | Electrochemical corrosion behaviour and prediction of corrosion rate for modified AA5083 alloys with REEs additions. | 201 |
| 4.7.1 | Introduction | 201 |
| 4.7.2 | Tafel extrapolation (TE) technique | 201 |
| 4.7.2.1 | Effect of Ce additions on the average corrosion rate of AA5083 alloy in 3.5% NaCl solution | 203 |
| 4.7.2.2 | Effect of Pr additions on the average corrosion rate of AA5083 alloy in 3.5% NaCl solution | 204 |
| 4.7.2.3 | Effect of (Ce+Pr) additions on corrosion rate for AA5083 alloy in 3.5% NaCl solution | 206 |
| 4.7.3 | Potentiodynamic polarization (PDP) technique | 207 |
| 4.7.3.1 | Impact of Ce additions on electrochemical corrosion of AA5083 in 3.5% NaCl solution | 211 |
| 4.7.3.2 | Impact of Pr additions on electrochemical corrosion of AA5083 in 3.5% NaCl solution. | 212 |
| 4.7.3.3 | Impact of Pr+Ce additions on electrochemical corrosion of AA5083 in 3.5% NaCl solution | 214 |
| 4.7.4 | Surface morphology | 215 |
| 4.8 | Total immersion corrosion tests and estimation of corrosion rate of the AA5083 alloy and the modified AA5083 alloys with REEs additions | 224 |
| 4.8.1 | Introduction | 224 |
| 4.8.2 | Estimating the average corrosion rate quantitatively by weight loss method | 224 |

| | | |
|----------|--|-----|
| 4.8.2.1 | Effect of Ce additions on the average corrosion rate of the AA5083 alloy | 224 |
| 4.8.2.2 | Effect of Pr additions on the average corrosion rate of the AA5083 alloy | 225 |
| 4.8.2.3 | Effect of Ce+Pr additions on the average corrosion rate of the AA5083 alloy | 227 |
| 4.8.3 | Characterization of corroded surfaces of the AA5083 alloys and the modified AA5083 alloys with Ce, Pr, and Ce+Pr additions | 229 |
| 4.8.3.1 | Visual inspection | 230 |
| 4.8.3.2 | Image processing technique | 232 |
| 4.8.3.3 | VPSEM/EDS analysis | 233 |
| 4.8.3.4 | Analysis of the corrosion layer | 236 |
| 4.9 | Immersion corrosion testing of the AA5083 alloy and the modified AA5083 alloys in 3.5% NaCl solution under high-speed conditions | 240 |
| 4.9.1 | Introduction | 240 |
| 4.9.3 | Morphological aspects | 242 |
| 4.10 | Prediction of erosion damage of AA5083 alloy and modified AA5083 alloys with REEs additions by a single-particle impact | 245 |
| 4.10.1 | Introduction | 245 |
| 4.10.2 | The quantitative evaluation for erosion Prediction | 245 |
| 4.10.2.1 | Effect of addition of Pr to the AA5083 alloy on the crater volume resulting from erosion by a single particle impact | 247 |
| 4.10.2.2 | Effect of addition Ce to the AA5083 alloy on the crater volume resulting from erosion by a single particle impact | 248 |
| 4.10.2.3 | Effect of addition Pr+Ce to the AA5083 alloy on the crater volume resulting from erosion by a single particle impact | 249 |
| 4.10.3 | Morphological aspects | 251 |
| 4.10.3.1 | Morphological aspect via low power optical microscope (LPOM) observation | 251 |
| 4.10.3.2 | Morphological aspects through an image processing technique | 253 |

| | | |
|----------|--|-----|
| 4.10.3.3 | Morphological aspect via SEM observation | 254 |
| 4.11 | The Charpy impact test | 255 |
| 4.11.1 | Introduction | 255 |
| 4.11.2 | Quantitative estimation of the influence of REE additions on Charpy v-notch impact toughness for the AA5083 alloy at room temperature and sub-zero temperature | 256 |
| 4.11.2.1 | Effect of Ce additions on the Charpy v-notch impact energy of the AA5083 alloy at room temperature and sub-zero temperature | 256 |
| 4.11.2.2 | Effect of Pr additions on the Charpy v-notch impact energy of the AA5083 alloy at room temperature and sub-zero temp. | 257 |
| 4.11.2.3 | Effect of Ce+Pr additions on the Charpy v-notch impact energy of the AA5083 alloy at room temperature and sub-zero temp | 258 |
| 4.11.3 | The correlation between (grain size - impact energy - REEs additions) for the modified AA5083 alloys | 261 |
| 4.12 | Tensile tests | 263 |
| 4.12.1 | Introduction | 263 |
| 4.12.2 | Effect of REE (Ce, Pr, and Ce+Pr) additions on tensile properties of the AA5083 alloy | 264 |
| 4.12.2.1 | Influence of additions of Pr on tensile properties of the AA5083 alloy | 264 |
| 4.12.2.2 | Influence of additions of the Ce on tensile properties of the AA5083 alloy | 265 |
| 4.12.2.3 | Influence of additions of the Ce+Pr on tensile properties of the AA5083 alloy | 266 |
| 4.12.3 | Application of (Hall-Petch) relationship to the modified AA5083 alloys with REE (Ce, Pr, and Ce+Pr) additions | 269 |
| 4.12.3.1 | Introduction | 269 |

| | | | |
|-------------------|----------|--|------------|
| | 4.12.3.2 | Application of H-P relationship to the modified AA5083 alloys with Ce additions | 270 |
| | 4.12.3.3 | Application of H-P Relationship to the modified AA5083 alloys with Pr additions | 271 |
| | 4.12.3.4 | Application of H-P Relationship to the modified AA5083 alloys with Ce+Pr additions | 272 |
| CHAPTER | 5 | CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORKS | 275 |
| | 5.1 | Conclusions | 275 |
| | 5.2 | Recommendations for Future Work | 277 |
| REFERENCES | | | 279 |
| APPENDICES | | | 319 |

LIST OF TABLES

| TABLE NO. | TITLE | PAGE |
|------------------|---|-------------|
| Table 2.1 | The designation system of Al-alloys according to the american aluminum association (AA), (Designation system-European Aluminum, the aluminium Automotive manual). | 8 |
| Table 2.2 | The common commercial aluminum-alloys (Designation system-European Aluminum, the aluminium Automotive manual). | 9 |
| Table 2.3 | The characteristics of the 5xxx series compared to other series. | 10 |
| Table 2.4 | Typical chemical composition for AA5083 alloy | 12 |
| Table 2.5 | Role of alloying elements in the AA5083 alloy | 13 |
| Table. 2.6 | Invariant equilibria in the Al corner of the Al-Mg-Mn system | 14 |
| Table 2.7 | The crystal structures, lattice parameters, and radii of (Ionic and metallic) REEs. | 19 |
| Table 2.8 | Lists of usage by application of REEs. | 20 |
| Table 2.9 | The common conventional methods for NDT. | 25 |
| Table 2.10 | Common methods to characterise precipitates in Al-alloys. | 35 |
| Table 2.11 | Homogenisation temperature for the Al-alloys series. | 36 |
| Table 2.12 | Potential IMCs in the 5xxx series Al-alloys. | 43 |
| Table 2.13 | Crystal Structures of the Different Phases in the Al-REEs Binary Systems. | 47 |
| Table 2.14 | The different ways of corrosion classification. | 51 |
| Table 2.15 | The common electrochemical techniques. | 67 |
| Table 2.16 | ASTM standards for the common mechanical tests of Al-alloys. | 78 |
| Table 3.1 | The chemical composition of the commercial AA5083 alloy | 88 |
| Table 3.2 | The targeted chemical composition of synthetic AA5083 alloys | 91 |
| Table 3.3 | The codes and classifications according to ASTM-G66 standards. | 113 |
| Table 3.4 | The parameters of the solid particle erosion test. | 116 |
| Table 4.1 | Description of the application of the PDCA cycle for continuous improvement in the AA5083 alloy casting process | 126 |

| | | |
|-----------|--|-----|
| Table 4.2 | Summary of NDT results to assess the quality of different casting methods for the cast AA5083 alloy | 132 |
| Table 4.3 | The IMC types found within the examined area for AA5083 alloy and modified AA5083 alloys with REE (Ce, Pr, Ce+Pr) additions, according to the VPSEM/EDS analysis | 156 |
| Table 4.4 | The results of the visual evaluation of the specimens after ASSET-Test (using the standard classification according to ASTM-G66) | 176 |

LIST OF FIGURES

| FIGURE NO. | TITLE | PAGE |
|-------------------|--|-------------|
| Figure 2.1 | Al-Mg phase diagram. | 11 |
| Figure 2.2 | Al-Mg-Mn isothermal section at 400 °C | 14 |
| Figure 2.3 | The melting and boiling points of the five unofficial groups of REEs. | 17 |
| Figure 2.4 | The five common crystal structure of REEs. | 19 |
| Figure 2.5 | Classification of die-casting according to Campbell, Cocks, and Nadca | 23 |
| Figure 2.6 | The most common alloying elements used for Al and Al- alloys. | 27 |
| Figure 2.7 | The surface appearance of AA5083 after homogenisation at 520°C for 12 hr (a) Appearance of cauliflower-like precipitates (b) Magnified appearance of cauliflower-like precipitates | 39 |
| Figure 2.8 | Factors affecting on the corrosion process of the materials | 50 |
| Figure 2.9 | An example of uniform corrosion | 52 |
| Figure 2.10 | An example of pitting corrosion | 53 |
| Figure 2.11 | The variation in the cross-sectional shape of the pits according to ASTM -G46 standard | 53 |
| Figure 2.12 | An example of exfoliation corrosion | 56 |
| Figure 2.13 | The ASSET result on the AA5083 plate | 58 |
| Figure 2.14 | An example of IGC intergranular corrosion | 59 |
| Figure 2.15 | An example of corrosion-erosion | 62 |
| Figure 2.16 | Effects of the intermetallic compound (IMC) on the growth of Al alloy oxide | 65 |
| Figure 2.17 | Tafel Extrapolation plot | 69 |
| Figure 2.18 | Types of erosion | 73 |

| | | |
|-------------|--|-----|
| Figure 2.19 | Schematic representation showing the characteristics of an impact crater on ductile materials produced by a normal impact using a spherical particle. | 75 |
| Figure 2.20 | Illustrates four sub-mechanisms by which solid particle impact erosion disconnected the materials from a target material. | 76 |
| Figure 2.21 | Comparison between yield strength (YS) and tensile strengths (TS) of commercial-grade (Al and Al-alloys) | 79 |
| Figure 3.1 | Flow chart of overall research methodology. | 89 |
| Figure 3.2 | The main steps for manufacturing the (a) crucible and (b) shell (used as a degassing chamber). (i) Preparation of a PVC foam mould (ii) Drying process after immersing the mould in the slurry mixture, then spraying it with fine-grained aluminosilicate ($Al_2O_3SiO_2$) (iii) The final product (crucible, shell). | 92 |
| Figure 3.3 | The setup for the in-situ casting process | 93 |
| Figure 3.4 | Flow chart presenting the sequential steps of the in-situ casting process. | 94 |
| Figure 3.5 | Dye penetrant kit (developer LD-3, penetrant P330A, and cleaner/remover). | 96 |
| Figure 3.6 | An example of a tested sample showing the spot of the flame as a result of chemical analysis by AAS. | 97 |
| Figure 3.7 | The homogenization experiment setup and the heating and cooling curves recorded during the homogenization experiments at 450 °C for 24hr. | 97 |
| Figure 3.8 | The main steps of the image processing technique using the ImageJ software to estimate the area fraction A_f (%) of IMCs for AA5083 alloys. | 99 |
| Figure 3.9 | Diagram showing the main steps for metallographic sample preparation | 101 |
| Figure 3.10 | The setup of accelerated electrochemical corrosion tests; (a) schematic and (b) experimental setup. | 105 |
| Figure 3.11 | The main steps of the laboratory full immersion corrosion test. | 106 |
| Figure 3.12 | The full immersion corrosion test of AA5083 alloy and modified AA5083 alloys with REEs. | 107 |

| | | |
|-------------|---|-----|
| Figure 3.13 | The overall configuration of the rotating disc apparatus (RDA) for corrosion test in 3.5%NaCl solution under high-speed condition (a) A simplified schematic of the experimental set-up (b) A photograph of the experimental setup. | 110 |
| Figure 3.14 | (a) An example of a sample for ASSET –Test. (b) samples preparation for the ASSET-Test (samples immersed vertically in glass jars containing the corrosive solution). | 114 |
| Figure 3.15 | The overall configuration of the device system of a single-particle erosion test (gas gun impact tester) that was designed locally at UTM University Production Lab. (a) Schematic drawing of the single-particle impact test. (b) Photograph of the experimental setup used for the single-particle impact test. | 116 |
| Figure 3.16 | Surface profilometer type E-35B | 118 |
| Figure 3.17 | (a) The geometry of the standard tensile specimen. (b) CNC machine used to prepare tensile samples. (c) Tensile test setup using a universal tensile testing machine (model: INSTRON-5982). | 119 |
| Figure 3.18 | Charpy impact testing machine (a) Standard Charpy V-notch impact test specimen (b) set-up at room temperature (c) Set-up at sub-zero temperature. | 121 |
| Figure 4.1 | Continuous improvement of the casting processes for the cast AA5083 alloys. | 127 |
| Figure 4.2 | This example shows a high-quality photograph of one of the cast AA5083 alloy sample that was produced by the fourth casting method. | 127 |
| Figure 4.3 | An example of the (VT) results for the cast AA5083 alloys that were produced by (a) the conventional casting method the first method, and (b) the in-situ casting technique with degassing - the fourth method. | 130 |
| Figure 4.4 | An example of the LT results for the cast AA5083 alloys that were produced by (a) the in-situ casting technique without degassing - the second method, and (b) the in-situ casting technique with a degassing-the fourth method. | 130 |
| Figure 4.5 | The common ultrasonic indications of four types of flaws found in castings | 131 |

| | | |
|-------------|--|-----|
| Figure 4.6 | An example of the UT results for the cast AA5083 alloys that were produced by (a) the in-situ casting technique without degassing - the second method, and (b) the in-situ casting technique with degassing - the fourth method | 131 |
| Figure 4.7 | The SEM images illustrate the homogenisation map of the microstructure evaluation for different homogenised and non-homogenised conditions for the AA5083 alloy | 137 |
| Figure 4.8 | The SEM images show the distribution of IMCs (white colour and dark colour positions) for AA5083 alloy in the case of (a) As-cast sample (b) As-homogenised (450°C/24h) sample | 138 |
| Figure 4.9 | The optical microscope image shows the emergence of brittle phases on the grain boundaries with subsequent crack initiation for AA5083 alloy homogenised at 500°C/8 hr | 138 |
| Figure 4.10 | An example showing the discontinuities and thinning of the Al (Mn, Fe) phase after homogenisation at 450°C/24 hr. | 139 |
| Figure 4.11 | Example of image processing using the 8-bit colour mode to estimate the area fraction of the selected phase: (i) SEM image, (ii) processing the SEM images and distinguishing the phases, (iii) estimation of the area fraction of white phases, and (iv) estimation of the area fraction of dark phases | 140 |
| Figure 4.12 | The total area fraction for IMCs of the AA5083 alloys (as-cast and as-homogenised) under various homogenisation conditions | 141 |
| Figure 4.13 | Hardness values and standard deviations of AA5083 alloy as-cast and as-homogenised under different homogenisation conditions | 143 |
| Figure 4.14 | A comparison between the XRD profiles of the AA5083 alloy (a) as-cast (before homogenization) and (b) as-homogenized (450°C/24 hr) | 145 |
| Figure 4.15 | The effect of different contents of Ce additions on the average grain size of the AA5083 alloy through the intercept method | 147 |
| Figure 4.16 | The effect of different contents of Pr additions on the average grain size of the AA5083 alloy via the intercept method | 148 |

| | | |
|-------------|---|-----|
| Figure 4.17 | The effect of different contents of Ce+Pr additions on the average grain size of the AA5083 alloy via the intercept method. | 150 |
| Figure 4.18 | Comparison between the contrast of the images using (a) BSE and (b) SE detector. | 153 |
| Figure 4.19 | (SEM/EDS) micrograph with corresponding EDS analysis of dominant IMC in the AA5083 alloy. | 157 |
| Figure 4.20 | (SEM/EDS) micrograph with corresponding EDS analysis of dominant IMCs in the modified AA5083 alloys with Ce additions. | 158 |
| Figure 4.21 | (SEM/EDS) micrograph with corresponding EDS analysis of dominant IMCs in the modified AA5083 alloys with Pr additions | 159 |
| Figure 4.22 | (SEM/EDS) micrograph with corresponding EDS analysis of dominant IMCs in the modified AA5083 alloys with (Ce+Pr) additions.. | 160 |
| Figure 4.23 | An example of IMC distribution in the modified AA5083 alloys (a) in the case of combined additions of Ce+Pr (overlapped IMCs) and (b) in the case of Ce additions individually (isolated IMCs). | 162 |
| Figure 4.24 | XRD patterns for AA5083 and modified AA5083 with different amounts of Ce additions. | 165 |
| Figure 4.25 | XRD patterns for AA5083 and modified AA5083 with different amounts of Pr additions. | 166 |
| Figure 4.26 | XRD patterns for AA5083 and modified AA5083 with different amounts of (Ce+Pr) additions. | 167 |
| Figure 4.27 | Distribution of IMCs for the modified AA5083 alloy (with various levels of Ce additions and with various levels of Pr additions). | 169 |
| Figure 4.28 | Distribution of IMCs for the modified AA5083 alloy with various levels of Ce+Pr additions. | 170 |
| Figure 4.29 | An example showing the main steps for estimating the area fraction (A_f) of the IMCs using ImageJ software. | 171 |
| Figure 4.30 | The effect of the variation in the content of Ce (wt.%) on the total area fraction of the IMCs for the modified AA5083 alloys. | 172 |

| | | |
|-------------|--|-----|
| Figure 4.31 | The effect of the variation in the content of Pr (wt%) on the total area fraction of the IMCs for the modified AA5083 alloys. | 172 |
| Figure 4.32 | The effect of the variation in the content of Ce+Pr (wt%) on the total area fraction of the IMCs for the modified AA5083 alloys. | 173 |
| Figure 4.33 | Photographs of control specimens after ASSET testing. (a) 5086-H116 alloy (as low susceptibility). (b) AA5456 alloy – rolled condition (as medium susceptibility). (c) AA5083 alloy – rolled and sensitised condition (as high susceptibility). | 174 |
| Figure 4.34 | Bar chart representing the corrosion rating levels of test samples for ASSET testing. | 176 |
| Figure 4.35 | Photographs showing the surface appearance of (a) AA5083, (b) modified AA5083 with 0.1wt% Ce, (c) modified AA5083 with 0.1wt% Pr, (d) modified AA5083 with 0.1wt% Ce + 0.1wt% Pr, and (e) modified AA5083 with 0.5wt% Ce + 0.5wt% Pr after ASSET testing | 177 |
| Figure 4.36 | Comparison of the ASSET-Test results for (a) the AA5083 alloy plate manufactured by ALUSTAR-TM Company and (b) the AA5083 alloy produced in the UTM foundry. | 178 |
| Figure 4.37 | The image processing of the standard photographs of the ASSET-Tests. | 180 |
| Figure 4.38 | An example of the image processing for samples of (a) the AA5083, (b) the modified AA5083 with 0.1wt% Pr, (c) the modified AA5083 with 0.1wt% Ce, and (d) the modified AA5083 with 0.1wt% Ce + 0.1wt% Pr that suffered from pitting corrosion after ASSET-Tests | 181 |
| Figure 4.39 | An example of SEM image (SE detector) showing fine pits around the periphery of a large pit. | 182 |
| Figure 4.40 | Typical examples of SEM images showing variation in the pit shape that appeared on the surface of specimens after ASSET testing: (a) semi-circular pit (b) crystallographic pitting (c) irregular pit (d) spiral pit (e) trench pit (f) longitudinal pit (g) elliptical pit. | 183 |
| Figure 4.41 | Model of the pits creation process by Fe-rich phases | 184 |

| | | |
|-------------|--|-----|
| Figure 4.42 | An example of detecting the remnants of IMCs types inside the pits using SEM/EDS technique | 186 |
| Figure 4.43 | VP-SEM image of crystallographic pitting on the surface of AA5083 alloy and EDS Spectra obtained on the pitting zone, after ASSET-Test | 187 |
| Figure 4.44 | Typical example of SEM images showing REE-rich phases as inert phases and the Fe-rich phases and Mg-rich phases as active phases. | 188 |
| Figure 4.45 | Effect of Pr additions on NAML T values of AA5083 alloy. | 192 |
| Figure 4.46 | Effect of Ce additions on NAML T values of AA5083 alloy. | 193 |
| Figure 4.47 | Effect of (Ce+Pr) additions on NAML T values of AA5083 alloy. | 195 |
| Figure 4.48 | A typical example of IGC attack for AA5083 alloy after NAML T. (a) VPSEM image and (b) processed image using ImageJ software. | 198 |
| Figure 4.49 | SEM images showing a comparison between the surface morphologies for AA5083 alloy and optimal modified AA5083 alloy (with 0.5wt% Ce + 0.5wt% Pr) after NAML T test. (a) AA5083 as-nonsensitized (b) AA5083 as-sensitized (c) modified AA5083 alloy with 0.5wt% Ce + 0.5wt% Pr as-nonsensitized (d) modified AA5083 alloy with 0.5wt% Ce + 0.5wt% Pr as-sensitized. | 199 |
| Figure 4.50 | An example of interrupting the β -phase network with REE-rich phases (a) (Ce, Pr-rich) phase (b) (Ce-rich) phase (c) (Pr-rich) phase. | 200 |
| Figure 4.51 | An example of the estimation of the corrosion rate via Tafel extrapolation method. | 202 |
| Figure 4.52 | Influence of Ce additions on the average corrosion rate of AA5083 alloy. | 204 |
| Figure 4.53 | Influence of Pr additions on the average corrosion rate of AA5083 alloy. | 205 |
| Figure 4.54 | Influence of Ce+Pr additions on the average corrosion rate of AA5083 alloy. | 207 |
| Figure.4.55 | Anodic polarization curves for AA5083 alloy and modified AA5083 with Pr additions in 3.5% NaCl solution at laboratory temperature $\approx 20 \pm 1^\circ\text{C}$ | 209 |

| | | |
|--------------|--|-----|
| Figure. 4.56 | Anodic polarization curves of AA5083 alloy and modified AA5083 with Ce additions in 3.5% NaCl solution at laboratory temperature $\approx 20 \pm 1^\circ\text{C}$ | 210 |
| Figure 4.57 | Anodic polarization curves of AA5083 alloy and modified AA5083 with (Ce+Pr) additions in 3.5% NaCl solution at laboratory temperature $\approx 20 \pm 1^\circ\text{C}$ | 210 |
| Figure 4.58 | Pitting potential (E _{pit}) and corrosion potential (E _{corr}) as a function of different Ce addition for the AA5083 alloys. | 212 |
| Figure 4.59 | Pitting potential (E _{pit}) and corrosion potential (E _{corr}) as a function of different Pr addition for the AA5083 alloys. | 213 |
| Figure 4.60 | Pitting potential (E _{pit}) and corrosion potential (E _{corr}) as a function of different Ce+Pr additions for the AA5083 alloys. 215 | |
| Figure 4.61 | An example of the pit ensued from IMC that acted as an anodic site for AA5083 alloy. (a) Schematic illustration showing the reaction between Al-alloy matrix and IMCs. (b) VPSEM image showing a pit that appears as a dark region that was obtained from the anodic site. (c) VPSEM image that has been treated by ImageJ software. (d) EDS spectrum acquired in the dark region. | 217 |
| Figure 4.62 | An example of the pit ensued from IMC, that acted as cathodic site for AA5083 alloy (a) Schematic illustration showing the reaction between the Al- alloy matrix and (Fe-rich) particle (b) the VPSEM image appears a pit that obtained from cathodic site (c) VPSEM image that has been treated by ImageJ software. (d) EDS spectrum acquired in the very light grey region. | 218 |
| Figure 4.63 | An example of the crystallographic pit that ensued in AA5083 alloy (a) VPSEM image with low magnification (b) VPSEM image with high magnification (a highly faceted structure is observed) (c) SEM image that was treated by ImageJ software | 219 |
| Figure 4.64 | An example of the presence of the (REEs-rich) intermetallic compound inside the crystallography pit. | 220 |
| Figure 4.65 | Illustrates an example of the stability of the (Ce - rich) particle, while the (Fe-rich) particle plays a crucial role in corrosion where it acts as a cathodic site. The attached EDS spectrum is the spectrum acquired from the particles. | 221 |
| Figure 4.66 | Illustrates an example of the stability of the (Pr-rich) particle, while the (Mg-rich) particle plays a crucial role in corrosion where it acts as an anodic site. The attached EDS spectrum is the spectrum acquired from the particle | 222 |

| | | |
|--------------|---|-----|
| Figure 4.67 | Illustrates an example of the stability of the (Ce-Pr- rich) particle, while the (Fe-rich) particle plays a crucial role in corrosion where it acts as a cathodic site. The attached EDS spectrum is the spectrum acquired on the particles. | 223 |
| Figure 4.68 | Effect of Ce additions on the average corrosion rate of AA5083 alloy | 225 |
| Figure. 4.69 | Effect of Pr additions on the average corrosion rate of AA5083 alloy. | 227 |
| Figure. 4.70 | Effect of Ce+Pr additions on the average corrosion rate of the AA5083 alloy. | 228 |
| Figure 4.71 | A photographic image of an example of a corroded AA5083 alloy sample after 70 days of immersion in stagnant 3.5% NaCl solution at 21 °C. | 231 |
| Figure 4.72 | 3D image of optical microscope showing a comparison of the features of corroded surfaces | 231 |
| Figure 4.73 | An example showing a comparison between the characteristics of corroded surfaces using ImageJ software for (a) the AA5083 alloy and (b) the modified AA5083 alloy with 0.5wt% Ce + 0.5wt% Pr additions. | 233 |
| Figure 4.74 | Morphology of corrosion of alloys (a) AA5083 and (b) modified AA5083 with 0.5wt% Ce + 0.5wt% Pr additions, showing the corrosion products after immersion in 3.5% NaCl solution for 70 days at 20°C. | 234 |
| Figure 4.75 | Breakdown of the corrosion deposit layer in specific regions | 235 |
| Figure 4.76 | An example of localised corrosion (pitting attack) attributed to (a) Fe-rich particle (b) Mg-rich particles. | 235 |
| Figure 4.77 | Pit morphology: (a) shallow/small (b) shallow/big (c) deep/small (d) deep/large | 236 |
| Figure 4.78 | X-ray diffraction patterns of the corrosion deposit layer for AA5083 alloy and modified AA5083 alloys with high levels of REE (Ce, Pr, and Ce + Pr) additions. | 239 |
| Figure 4.79 | The average corrosion rate of AA5083 alloy and the modified AA5083 alloys with REE (Ce, Pr, Ce+Pr) additions in 3.5% NaCl solution under high-speed conditions (33km/h) after a period of 50 hr. | 241 |
| Figure 4.80 | Appears the surface morphology of the samples, after exposed to corrosion test in 3.5% NaCl solution under high speed condition for 50hr, at room temperature (a) AA5083 alloy before the test (b) AA5083 alloy (b) after the test (c) modified AA5083 alloy with | |

| | | |
|--------------|---|-----|
| | 1.0wt.% Pr addition (d) modified AA5083 alloy with 1.0wt. % Ce addition (e) modified AA5083 alloy with (0.5wt% Ce + 0.5wt%Pr) addition | 243 |
| Figure 4.81 | VPSEM micrograph showing an example of slight elongation of the pits on the surface of the alloy in the opposite direction of the motion of the sample | 244 |
| Figure 4.82 | The variation in the average volume of the craters vs. wt. % of Pr content. | 248 |
| Figure 4.83 | The variation in the average craters volume vs. wt. % of Ce content | 249 |
| Figure 4.84 | The variation in the average volume of the craters vs. wt. % of Ce+Pr content. | 250 |
| Figure 4.85 | An example of the craters that were formed as a result of steel ball impingement | 251 |
| Figure 4.86 | The plastic deformation as a result of single-particle impact (steel ball) at normal incidence (one impingement). (i) crater has a uniform plastic deformation, and (ii) crater has non-uniform plastic deformation. | 252 |
| Figure 4.87 | An example of surface morphology of a repeated single particle impacts (multi impingement). | 252 |
| Figure 4.88 | The two types of plastic deformation as a result of a single particle impact (steel ball) at normal incidence. (i) the uniform plastic deformation and (ii) non-uniform plastic deformation. | 253 |
| Figure 4.89 | The lip formed around the crater appears almost entirely circular (i) in the case of a single particle impact and (ii) in the case of the repeated impact of a single solid particle. | 254 |
| Figures 4.90 | The typical appearance of the surface at high magnification via VPSEM free from cracking or cutting initiation (a) for AA5083 and (b) for modified AA5083 alloy with 0.5wt% Ce + 0.5wt% Pr additions. | 255 |
| Figure 4.91 | The average absorbed energy for AA5083 alloys vs. Ce content at room temperature and sub-zero temperature. | 257 |
| Figure 4.92 | The average absorbed energy for AA5083 alloys vs. Pr content at room temperature and below zero. | 258 |
| Figure 4.93 | The average absorbed energy for AA5083 alloys vs. Ce+Pr content at room temperature and sub-zero temperature. | 259 |
| Figure 4.94 | The correlation between (grain size - impact energy - wt. % of Ce) for modified AA5083 alloys. | 262 |
| Figure.4.95 | The correlation between (grain size - impact energy - wt. % of Pr) for modified AA5083 alloys. | 262 |

| | | |
|---------------|---|-----|
| Figure. 4.96. | Correlation between (grain size - impact energy – wt. % of (Ce+ Pr)) for modified AA5083 alloys | 263 |
| Figure 4.97 | The histogram for the comparison of yield strength (σ_y) and the ultimate tensile strength (σ_{UTS}) values for the modified AA5083 alloys with different levels of Pr additions. | 265 |
| Figure 4.98 | The histogram for the comparison of yield strength (σ_y) and the ultimate tensile strength (σ_{UTS}) values for the modified AA5083 alloys with different levels of Ce addition. | 266 |
| Figure 4.99 | The histogram for the comparison of yield strength (σ_y) and the ultimate tensile strength (σ_{UTS}) values for the modified AA5083 alloys with different levels of Pr+Ce additions | 267 |
| Figure 4.100 | Hall-Petch plot (yield strength versus inverse square root of the average grain size) for the modified AA5083 alloys with Ce additions. | 270 |
| Figure 4.101 | Hall-Petch plot (yield strength versus inverse square root of the average grain size) for the modified AA5083 alloys with Pr additions. | 271 |
| Figure 4.102 | Hall-Petch plot (yield strength versus inverse square root of the average grain size) for the modified AA5083 alloys with Pr+Ce additions. | 272 |

LIST OF ABBREVIATIONS

| | | |
|-------------------|---|--|
| ISO | - | International Organization For Standardization |
| ASTM | - | American Society For Testing And Materials |
| REEs | - | Rare Earth Elements |
| LREEs | - | Light Rare Earth Elements |
| HREEs | - | Heavy Rare Earth Elements |
| NDT | - | Non-Destructive Testing |
| VT | - | Visual Inspection |
| LT | - | Liquid Penetrant Testing |
| UT | - | Ultrasonic Testing |
| IMCs | - | Intermetallic Compounds |
| NAMLT | - | Nitric Acid Metal Loss Test |
| ASSET | - | Assessment Of The Exfoliation Test |
| IGC | - | Intergranular Corrosion |
| IGSCC | - | Intergranular Stress Corrosion Cracking |
| PDP | - | Potentiodynamic Polarization |
| TE | - | Tafel Extrapolation |
| EFC | - | Exfoliation Corrosion |
| E _{corr} | - | Corrosion Potential |
| i _{corr} | - | Corrosion Current Density |
| E _{pit} | - | Pitting Potential |
| I _{pass} | - | Passivation Current Density |
| WE | - | Working Electrode |
| RE | - | Reference Electrode |
| CE | - | Counter Electrode |
| SCE | - | Saturated Calomel Electrode |
| CR | - | Corrosion Rate |
| CNC | - | Computer Numerical Control |
| XRD | - | X-Ray Diffraction |

| | | |
|-------|---|---|
| OM | - | Optical Microscopy |
| LOM | - | Low Power Magnification Light Optical Microscope |
| HOM | - | High Power Magnification Light Optical Microscope |
| EDS | - | Energy Dispersive X-Ray Scanning |
| VPSEM | - | Variable Pressure-Scanning Electron Microscope |
| GZ | - | Grain Size |
| ASL | - | Altered Surface Layer |
| TS | - | Tensile Strength |
| UTS | - | Ultimate Tensile Strength |
| Wt. % | - | Weight Percentage |
| rpm | - | Rotation per Minute |

LIST OF APPENDICES

| APPENDIX | TITLE | PAGE |
|-----------------|--|-------------|
| Appendix A | Criticality matrix, showing (the supply risk vs. importance to clean energy) for rare earth elements REEs. | 318 |
| Appendix B | Proposed classification of defects by AIM (Italian Association of Metallurgy) | 319 |
| Appendix C | Phase and microstructure of Al with rare earth elements REEs. | 320 |
| | C-1 Similarities and trends in Phase diagrams of rare-earth elements with aluminium (Al-REEs phase diagrams). | 320 |
| | C-2 Calculated binary phase diagram for Al-Pr system via a thermodynamic database | 321 |
| | C-3 The calculated isothermal section of the Al-Mg-Pr ternary system at $T = 673 \text{ K}$. | 321 |
| | C-4 Calculated binary phase diagram for Al-Ce system via a thermodynamic database | 322 |
| | C-5 The calculated isothermal section of the Al-Mg-Ce ternary system at 673K | 322 |
| Appendix D | Inspection certification for the chemical composition of AA5083 used in the research | 323 |
| Appendix E | E-1 Screen view of IMT i-Solution software program as an example of using the intercept method for estimating the grain size of the AA5083 alloys | 324 |
| | E-2 Screen view for illustrating an example of measuring the crater diameter via the optical microscope (OM) combined with advanced software (The i-Solutions DT software package). | 324 |

| | | |
|------------|--|-----|
| Appendix F | Cause and Effect (CAE) diagram as a strategy tool for identifying prevention of the casting defects | 325 |
| Appendix G | The chemical composition of the modified alloys used in the research | 326 |
| Appendix H | The estimated grain size of the AA5083 alloy and the modified AA5083 alloys with REEs (REEs = Ce, Pr, and Ce+Pr) additions via the intercept method. | 327 |
| Appendix I | The average of total area fraction (Af %) of existing IMCs in AA5083 alloys and the modified AA5083 alloys. Vs. the addition of quantities of REEs (REEs = Ce, Pr, and Ce+Pr), which were estimated by ImageJ software | 328 |
| Appendix J | J1 Quantitative results of NAML-T-Test for AA5083 alloy and modified AA5083 alloys with REEs (REEs = Ce, Pr, and Ce+Pr) additions. | 329 |
| | J-2 The average corrosion rates results estimated by Tafel method for AA5083 alloy and modified AA5083 alloys with REEs (REEs= Ce, Pr, and Ce+Pr) additions. | 330 |
| | J-3 Electrochemical data (E_{corr} , E_{pit} , and I_{corr}) extracted from anodic polarization curves for synthetic alloys. | 331 |
| | J-4 Average values of corrosion rate estimated by weight loss (WL) method for AA5083 alloys and modified AA5083 alloys with addition Ce, Pr, and Ce+Pr after exposed to 70 days of full immersion in 3.5 % NaCl, at $21^{\circ}\text{C} \pm 2$. | 332 |
| | J-5 Average corrosion rate for the samples in 3.5 NaCl solutions under high speed (33 km/h) condition after a period of 50 hr, estimated via the weight loss method | 332 |
| Appendix K | The chemical composition of the corrosion deposits layer of the tested samples obtained by utilizing EDS analysis | 333 |

| | | |
|------------|--|-----|
| Appendix L | Estimated average diameter, average depth, and the average volume of the plastic deformation for AA5083 alloy and modified AA5083 alloys due to the erosion by a solid particle impact | 334 |
| Appendix M | The results obtained from Charpy tests on the AA5083 alloys and the AA5083 modified alloys, at room temperature and at temperatures below zero | 335 |
| Appendix N | Summary of the tensile properties results obtained for AA5083 and modified AA5083 alloys at room temperature | 336 |
| Appendix O | Publications | 337 |

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Newly modified alloys with exceptional characteristics are created every day for specific applications. The AA5083 aluminium-magnesium-manganese alloy is generally classified as a non-heatable alloy. It is characterised by certain unique properties that have made it one of the most important and commercially popular alloys. AA5083 has a low density and a high strength-to-weight ratio, has ideal welding properties, is easy to machine and form medium strength, is able to resist corrosion in marine and industrial environments, and is available at a reasonable cost. These particular properties make it a clear choice for a variety of engineering applications such as marine technology (shipbuilding materials), the automotive industry, the aerospace industry, pressure vessels, armoured vehicles, and armour plate (Kaibyshev *et al.*, 2003; Liu *et al.*, 2017; Sunny *et al.*, 2013).

On the other side, AA5083 alloy is susceptible to intergranular corrosion (IGC) and intergranular stress corrosion cracking (IGSCC) when exposed to temperatures between 50°C and 200°C. This is due to sensitisation process, which is a consequence of the formation of β -phase Al_3Mg_2 at the grain boundary. This phenomenon also has an adverse effect on mechanical properties in which the β -phase leads to a decline in the hardness and strength of the material because of a reduction of the Mg concentration in the aluminium solid solution (Oguocha *et al.*, 2008; Searles *et al.*, 2001; Vetrano *et al.*, 1997). In addition, the AA5083 alloy is susceptible to localised corrosion in NaCl solution in the form of pitting corrosion, which occurs as a result of the formation of Fe-rich phases such as $\text{Al}_6(\text{Fe}, \text{Mn})$ and $\text{Al}(\text{Mn}, \text{Fe}, \text{Cr})$, as well as Mg-rich phases such as Mg_2Si (Aballe *et al.*, 2001; Lucadamo *et al.*, 2006; Yasakau *et al.*, 2007). This phenomenon becomes more pronounced when the alloy is subjected

to high-speed conditions (Jafarzadeh *et al.*, 2009; Jo *et al.*, 2002). The above factors limit the use of the AA5083 alloy in several critical applications.

To address the limitations, the microstructure, mechanical properties, and corrosion resistance of aluminum and aluminum alloys, it is improved by adding an appropriate amount of rare earth elements (REEs: Ce, Sc, Pr, La, Er, Y, Nd, Eu, Pm, Gd, Dy, Ho, Tb, Tm, Yb, Lu, and Sm), as indicated by various previous studies (Jin, 2012; Umarova, 2017). Therefore, the addition of REEs to AA5083 is a promising topic. Ce has successfully been used on AA5083 and other Al alloys. The addition was made on individual elements in the range of 0.1wt% to 0.6wt%, which enabled the mechanical properties (hardness, tensile strength, and elongation) to be enhanced. Additionally, praseodymium (Pr), may provide a similar effect since it belongs to the light rare-earth elements (LREEs) as Ce.

Several studies have been conducted to determine the effect of Pr addition as individual alloy element to Al alloy such as Al-Cu, Al metal matrix composites (Al₂O₃-SiO₂) and Ce-Pr combination on Al-7Si-0.7Mg alloy and Al-8.52Zn-2.41Mg-2.1Cu-0.16Zr. In general, results showed that the addition of Pr as individual elements improved the microstructure and mechanical properties. Addition of a combination of Ce-Pr resulted in, not just microstructure and mechanical properties but also enhanced the exfoliation corrosion (EXCO) and IGC resistance.

In short, the REEs are critically important as alloying elements in modifying Al-alloys to enhance its microstructure, mechanical properties, and corrosion resistance. The optimal addition of REEs varies between different elements and alloys, such that the selection of the optimal quantity of the addition depends on the type of element added as well as the alloy type (a type of the modified alloy). In addition, previous studies have shown that the addition of REEs as a mixture achieves more benefits than individual REE additions. However, the researches were mainly emphasised on investigating the properties by individual element addition. Therefore, this research was aimed at improving the microstructure, mechanical properties, and corrosion behaviour of AA5083 by adding rare earth elements in combined form. The research investigated the addition of a combination of Ce-Pr in the amount of 0.5wt%

each. In addition, the investigation was also conducted on the addition of individual element Ce and Pr in the amount ranging between 0.1wt% and 1wt%.

1.2 Problem statement

Aluminium-magnesium-manganese (Al-Mg-Mn) alloys in particular AA5083 alloy has good corrosion resistance where its applications are best used in the marine environment and industrial atmospheres. However, its medium mechanical strength (Huang *et al.*, 2017) and its susceptibility to localised corrosion attack in a corrosive medium (NaCl), which are both caused by the presence of Mg-rich and Fe-rich phases (Aballe *et al.*, 2001; Czechowski, 2005; Yasakau *et al.*, 2007) has limits its uses in many applications. This phenomenon becomes more pronounced when the alloy is subjected to high-speed conditions (Gehring Jr, 1979; Gehring Jr and Peterson, 1981). Another problem is its susceptibility to IGC and IGSCC when exposed to temperatures between 50°C and 200°C (Jones *et al.*, 2001; Oguocha *et al.*, 2008; Searles *et al.*, 2001) resulting from precipitation of the β -phase (Mg_2Al_3) along the grain boundary, which acts as an anodic site relative to the AA5083 alloy matrix.

Many elements have been used to improve the mechanical properties of aluminium alloys. However, research has shown that besides other elements such as Zr, Sc, and Sr, REEs have been added to aluminium alloy to improve its microstructure, mechanical properties, and corrosion resistance. These include Nd, Er, Ce, La, and Pr. Ce has been widely researched in altering the microstructure and mechanical properties of Al-Mg alloys. However, the investigations were limited to microstructure and mechanical properties studies only. For marine and industrial environment applications particularly corrosive environment, where AA5083 alloy is much suited, very limited works have been carried out to investigate the effect of REEs addition. Nd, Sc, and Ce as an individual element added in the range of 0.1wt% to 0.5wt% to AA5083 alloy proved to refine the grain size and thus enhance the mechanical properties of the alloy even though REEs added to other Al alloys in the amount of up to 1wt% were found to produce a better effect. It indicated that the

capability of the REEs either being individually added or in combination to enhancing the microstructure, mechanical properties and corrosion resistance on AA5083 has not been fully explored. Therefore, further investigation is needed to explore the possibility of adding REEs on the microstructure, mechanical properties, and corrosion behaviour of AA5083 alloy.

1.3 Research objectives

The overall objectives of this research were to evaluate the influence of certain REE (Ce, Pr, and Ce+Pr) additions on the microstructure, mechanical properties, and corrosion behaviour of newly developed AA5083 alloys. Specific objectives are as follows:

1. To determine the effect of different amounts of Ce, Pr, and a mixture of Pr and Ce additions on the microstructure and phase/compound of the modified AA5083 alloy.
2. To investigate the mechanical properties of the modified AA5083 alloy using tensile and Charpy tests
3. To investigate the influence of different amounts of Ce, Pr, and a mixture of Pr and Ce additions on the corrosion behaviour of the modified AA5083 alloys.

1.4 Scope of the research

The scope of the research is designed to satisfy the research objectives as follows:

1. Fabricate three types of modified AA5083 alloy via the in-situ casting technique using an induction furnace in a controlled atmosphere. The three modified AA5083 alloys are:
 - i. AA5083 + xCe alloys {x = 0.1, 0.3, 0.5, 0.7 and 1.0wt%}
 - ii. AA5083 + yPr alloys {y = 0.1, 0.3, 0.5, 0.7 and 1.0wt%}

- iii. AA5083 + Mm alloys ($Mm = xCe + yPr$), where $(x:y) = \{(0.1:0.1), (0.1:0.3), (0.1:0.5), (0.3:0.1), (0.3:0.3), (0.3:0.5), (0.5:0.1), (0.3:0.5)\}$ and $(0.5:0.5)\}$
2. Perform non-destructive testing (NDT: visual inspection, VT; liquid penetrant testing, LT; and ultrasonic testing, UT) for cast product (modified AA5083 alloy) quality assessment.
3. Perform the homogenisation process at 450°C for 24hr by using an electric furnace in a controlled atmosphere.
4. Perform microstructure characterisation on the modified AA5083 alloys using an optical microscope, a variable pressure scanning electron microscope (VPSEM) with energy disperse x-ray spectroscopy (EDS), and x-ray diffraction analysis (XRD) as well as image processing techniques using Image J Software.
5. Perform mechanical tests for the modified AA5083 alloys, including tensile tests at room temperature and Charpy impact tests at both room temperature and subzero temperature, according to ASM standard procedures.
6. Perform corrosion tests for the modified AA5083 alloys, including IGC susceptibility by mass loss after exposure to nitric acid test (NAMLT), exfoliation and pitting corrosion susceptibility (ASSET-Test), and accelerated electrochemical corrosion testing through potentiodynamic polarization (PDP) and Tafel extrapolation (TE) techniques. The erosion test is done by solid particle impingement at normal incidence, full immersion corrosion test, and full immersion corrosion test under high-speed conditions (corrosion-erosion).

1.5 Significance of the research

This study is an effort to provide significant information about the microstructure, mechanical properties, and corrosion behaviour of the AA5083 alloy and the modified AA5083 alloys with the REEs (Ce and Pr) in the form of individual or combined additions. The findings of this study will benefit the industries that use the AA5083 alloy in their applications, such as the shipbuilding, automotive, pressure vessel, armour plate, and aerospace industries. Positive results are expected from the implementation of the microalloying technique via Pr, Ce, and Pr + Ce additions. The

outcome will extend the scope of application of the modified AA5083 alloys and will enhance the importance of using REE additives as alloying elements in the development of the AA5083 alloy. Future researchers are encouraged to utilise the microalloying technique using REE additions.

1.6 Thesis organisation

This thesis is organized into five chapters. The **first chapter** is an introduction to the study. It aims to provide a brief overview of the research, including the research background, problem statement, research objectives, scope of the research, and significance of the research. The **second chapter** is a comprehensive literature review related to the study topic (microstructure, mechanical properties, and corrosion behaviour of AA5083 alloys modified with REEs). The **third chapter** describes the research methodology for this study and presents a detailed description of the experimental procedures. In the **fourth chapter**, the results and discussion for the experimental work are presented in five phases according to the sequence in the third chapter. The **fifth chapter** provides conclusions based on the results and discussions. Recommendations for further study based on current research gaps that were recognized during this study will be highlighted in the fifth chapter.

REFERENCES

- Aballe, A., Bethencourt, M., Botana, F., Cano, M., and Marcos, M. (2001a) 'Localized alkaline corrosion of alloy AA5083 in neutral 3.5% NaCl solution', *Corrosion Science*, 43(9), 1657-1674.
- Aballe, A., Bethencourt, M., Botana, F., Cano, M., and Marcos, M. (2003) 'Influence of the cathodic intermetallics distribution on the reproducibility of the electrochemical measurements on AA5083 alloy in NaCl solutions', *Corrosion Science*, 45(1), 161-180.
- Aballe, A., Bethencourt, M., Botana, F., and Marcos, M. (2001b) 'CeCl₃ and LaCl₃ binary solutions as environment-friendly corrosion inhibitors of AA5083 Al-Mg alloy in NaCl solutions', *Journal of Alloys and Compounds*, 323, 855-858.
- Aballe, A., Bethencourt, M., Botana, F., Marcos, M., and Sánchez-Amaya, J. (2004) 'Influence of the degree of polishing of alloy AA 5083 on its behaviour against localised alkaline corrosion', *Corrosion Science*, 46(8), 1909-1920.
- Ahmad, Z., and Aleem, B. A. (2002) 'Degradation of aluminum metal matrix composites in salt water and its control', *Materials & Design*, 23(2), 173-180.
- Aiura, T., Sugawara, N., and Miura, Y. (2000) 'The effect of scandium on the as-homogenized microstructure of 5083 alloy for extrusion', *Materials Science and Engineering: A*, 280(1), 139-145.
- Al-Marahleh, G. (2006) 'Effect of heat treatment on the distribution and volume fraction of Mg₂Si in structural aluminum alloy 6063', *Metal Science and Heat Treatment*, 48(5-6), 205-209.
- Alam, M. A., Zuga, L., and Pecht, M. G. (2012) 'Economics of rare earth elements in ceramic capacitors', *Ceramics International*, 38(8), 6091-6098.
- Alkanhal, T. A. (2014) 'Image processing techniques applied for pitting corrosion analysis', *International Journal of Research in Engineering and Technology*, 5(2), 2319-1163.
- Allachi, H., Chaouket, F., and Draoui, K. (2010) 'Protection against corrosion in marine environments of AA6060 aluminium alloy by cerium chlorides', *Journal of Alloys and Compounds*, 491(1-2), 223-229.
- Allgaier, M. (1991) 'Visual testing: method with a future', *Materials Evaluation*, 49(9), 1186-1187.

- Anasyida, A., Daud, A., and Ghazali, M. J. (2009) 'Dry sliding wear behaviour of Al-4Si-4Mg alloys by addition of cerium', *International Journal of Mechanical and Materials Engineering*, 4(2), 127-130.
- Andrews, D. (1981) 'An analysis of solid particle erosion mechanisms', *Journal of Physics D: Applied Physics*, 14(11), 1979.
- Anwar, S., Axinte, D., and Becker, A. (2011) 'Finite element modelling of a single-particle impact during abrasive waterjet milling', *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 225(8), 821-832.
- Apelian, D., Sigworth, G. K., and Whaler, K. (1984) 'Assessment of grain refinement and modification of Al-Si foundry alloys by thermal analyses', *AFS Trans*, 92(2), 297-307.
- Ashby, M. F. (1972) 'A first report on deformation-mechanism maps', *Acta Metallurgica*, 20(7), 887-897.
- American Society for Testing and Materials (1995). *ASTM SE-165*. ASTM International, West Conshohocken, PA.USA
- American Society for Testing and Materials (2013). *ASTM G66-99*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (1994). *ASTM G102*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2015). *ASTM G112*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2015). *ASTM MNL20*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2005). *ASTM G46*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2004). *ASTM E8*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (1972). *ASTM STP516*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2011). *ASTM E3-11*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2010). *ASTM E112-10*. ASTM International, West Conshohocken, PA.USA.

- American Society for Testing and Materials (2002). *ASTM B 557M-02a*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (1997). *ASTM E23*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2003). *ASTM E92*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2004). *ASTM G1-03*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2006). *ASTM G102-89*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2009). *ASTM G59-97*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2001). *ASTM G34-01*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2004a). *ASTM E112-96*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2004b). *ASTM G31-72*. ASTM International, West Conshohocken, PA.USA.
- American Society for Testing and Materials (2004c). *ASTM G67*. ASTM International, West Conshohocken, PA.USA.
- Balasubramanian, R., Vijayarathi, P., and Venkatamuni, D. T. (2015) 'Experimental investigation of microstructure and mechanical properties of TIG welded aluminium alloys', *Journal of Advance Research in Mechanical & Civil Engineering*, 2(3), 01-10.
- Attallah, M. (2008) *Microstructure Property Development in Friction Stir Welds of Aluminim Based Alloys*. PhD Thesis, University of Birmingham, UK.
- Banerjee, S. (2011) *Modeling and Simulation of Solid Particle Erosion of Protective Films*. MSc Thesis, Texas A & M University, USA.
- Barbucci, A., Cerisola, G., Bruzzone, G., and Saccone, A. (1997) 'Activation of aluminium anodes by the presence of intermetallic compounds', *Electrochimica Acta*, 42(15), 2369-2380.
- Bardal, E., and Drugli, J. (2004). Corrosion detection and diagnosis, Materials science and engineering, vol. 3, Developed under the Auspices of the UNESCO, Eolss

- Publishers, Oxford, UK. <http://www.eolss.net/sample-chapters/c05/e6-36-04-04.pdf>
- Barenji, R. V. (2017) 'Casting fluidity, viscosity, microstructure and tensile properties of aluminum matrix composites with different Mg₂ Si contents', *Rare Metals*, 36(4), 1-10.
- Barrett, S. D., and Dhesi, S. S. (2001). *The structure of rare-earth metal surfaces*, 1st edn. World Scientific. Imperial college press, London, UK, 1-191.
- Beaudry, B., and Gschneidner Jr, K. (1978). Handbook on the physics and chemistry of rare earths, Vol. 1. Preparation and basic properties of the rare earth metals' Elsevier, North Holland, Amsterdam, 173-232.
- Bellinger, N., Komorowski, J., Liao, M., Carmody, D., Foland, T., and Peeler, D. (2002). 'Preliminary Study into the Effect of Exfoliation Corrosion on Aircraft Structural Integrity', In: 6th joint FAA/DOD/NASA Aging Aircraft Conference, held September 7-11, 2002. San Francisco, USA, 16-19.
- Berger, H. (Ed.). (1977). *Non-destructive testing standards: A review: a symposium (No. 624)*. 2nd edition, American society for testing and materials, Philadelphia, PA, USA, 1-317
- Berkovic, L., Ryckaert, R., Chabotier, A., Coghe, F., and Rabet, L. (2009). Modeling of high temperature Hopkinson tests on AA5083 and Ti6Al4V. *In Proceedings of DYMAT, International Conference on the Mechanical and Physical Behaviour of Materials Under Dynamic Loading*. September 7-11, 2009. Belgium, 1663-1668.
- Bessone, J., Salinas, D., Mayer, C., Ebert, M., and Lorenz, W. (1992) 'An EIS study of aluminium barrier-type oxide films formed in different media', *Electrochimica Acta*, 37(12), 2283-2290.
- Bethencourt, M., Botana, F., Calvino, J., Marcos Bárcena, M., Pérez, J., and Rodriguez, M. (1998) 'The influence of the surface distribution of Al₆(MnFe) intermetallic on the electrochemical response of AA5083 aluminium alloy in NaCl solutions', *Materials Science Forum*, 289, 567-574.
- Bhosale, S. D., Shilwant, S., and Patil, S. (2013) 'Quality improvement in manufacturing processes using SQC tools', *International Journal of Engineering Research and Applications*, 3(3), 832-837.

- Binnemans, K., Jones, P. T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., et al. (2013). 'Recycling of rare earths: a critical review', *Journal of Cleaner Production*, 51, 1-22.
- Biol, Y. (2004) 'The effect of homogenization practice on the microstructure of AA6063 billets', *Journal of Materials Processing Technology*, 148(2), 250-258.
- Bitter, J. (1963a) 'A study of erosion phenomena', part I. *Wear*, 6(1), 5-21.
- Bitter, J. (1963b) 'A study of erosion phenomena', Part II. *Wear*, 6(3), 169-190.
- Boucheur, M., Hamana, D., and Laoui, T. (1996) 'GP zones and precipitate morphology in aged Al-Mg alloys', *Philosophical Magazine A*, 73(6), 1733-1740.
- Brůna, M., and Sládek, A. (2011) 'Hydrogen analysis and effect of filtration on final quality of castings from aluminium alloy AlSi₇Mg_{0.3}', *Archives of Foundry Engineering*, 11(1), 5-10.
- Brunelli, K., Magrini, M., and Dabala, M. (2012) 'Method to improve corrosion resistance of AA 5083 by cerium-based conversion coating and anodic polarisation in molybdate solution', *Corrosion Engineering, Science and Technology*, 47(3), 223-232.
- Buschow, K. (1977) 'Intermetallic compounds of rare-earth and 3d transition metals', *Reports on Progress in Physics*, 40(10), 1179.
- Cáceres, C. (1998) 'A rationale for the quality index of Al-Si-Mg casting alloys', *International Journal of Cast Metals Research*, 10(5), 293-299.
- Caceres, C., and Selling, B. (1996) 'Casting defects and the tensile properties of an AlSiMg alloy', *Materials Science and Engineering: A*, 220(1-2), 109-116.
- Callister, W. D., and Rethwisch, D. G. (2011). *Materials science and engineering* Vol. 5, 2nd Edn. John Wiley & Sons. USA, 100-555.
- Campbell, F. C. (2013). *Inspection of metals: understanding the basics*. 2nd edn. ASM International, Material Park, Ohio, USA, 1-413.
- Campbell, F. C. (2008). *Elements of metallurgy and engineering alloys*. 1st edn. ASM International. Material Park, Ohio, USA, 1-513.
- Campbell, J. (2002). *The new metallurgy of cast metals*. 2nd edn. Butterworth Heinemann: Oxford, 17-345.

- Campestrini, P., Van Rooijen, H., Van Westing, E., and De Wit, J. (2000) 'Influence of quench delay time on the corrosion behavior of aluminium alloy 2024', *Materials and Corrosion*, 51(9), 616-627.
- Carroll, M., Gouma, P., Daehn, G., and Mills, M. (2001) 'Effects of minor Cu additions on a Zn-modified Al-5083 alloy', *Materials Science and Engineering: A*, 319, 425-428.
- Carroll, M., Gouma, P., Mills, M., Daehn, G., and Dunbar, B. (2000) 'Effects of Zn additions on the grain boundary precipitation and corrosion of Al-5083', *Scripta Materialia*, 42(4), 335-340.
- Cavanaugh, M., Birbilis, N., Buchheit, R., and Bovard, F. (2007) 'Investigating localized corrosion susceptibility arising from Sc containing intermetallic Al₃Sc in high strength Al-alloys', *Scripta Materialia*, 56(11), 995-998.
- Cenna, A., Williams, K., and Jones, M. (2011) 'Analysis of impact energy factors in ductile materials using single particle impact tests on gas gun', *Tribology International*, 44(12), 1920-1925.
- Chandrashekar, T., Muralidhara, M., Kashyap, K., and Rao, P. R. (2009) 'Effect of growth restricting factor on grain refinement of aluminum alloys', *The International Journal of Advanced Manufacturing Technology*, 40(3-4), 234-241.
- Chang, J., and Chuang, T. (1999) 'Stress-corrosion cracking susceptibility of the superplastically formed 5083 aluminum alloy in 3.5 pct NaCl solution', *Metallurgical and Materials Transactions A*, 30(12), 3191-3199.
- Chang, J., and Chuang, T. (2000) 'The degradation of corrosion resistance for Al 5083 alloy after thermal and superplastic forming processes', *Journal of Materials Engineering and Performance*, 9(3), 253-260.
- Chang, X., Wang, J., Shao, H., Wang, J., Zeng, X., Zhang, J., et al. (2008) 'Corrosion and anodic behaviors of pure aluminum in a novel alkaline electrolyte', *Acta Physico-Chimica Sinica*, 24(9), 1620-1624.
- Changzhong, Z., and Zhonghan, L. (1984) 'Rare-Earth Metals and their Applications in Aviation', Foreign Technology Div Wright-Patterson AFB OH. Document Number) FTD-ID (RS) T-0842-84), 1-10.
- Chattoraj, I. (2007) 'Fundamentals of corrosion and its prevention', *Industrial Corrosion Evaluation &- Mitigation*, 1-17.

- Chawla, K.K and Meyers, M.A (2009). Mechanical behavior of materials, 2nd edn. Cambridge University press. UK, 1-477.
- Chen, B., Li, C.-H., He, S.-C., Li, X.-I., and Lu, C. (2014) 'Corrosion behavior of 2099 Al-Li alloy in NaCl aqueous solution', *Journal of Materials Research*, 29(12), 1344-1353.
- Chen, C., and Mansfeld, F. (1997) 'Corrosion protection of an Al 6092/SiCp metal matrix composite', *Corrosion Science*, 39(6), 1075-1082.
- Chen, K., Fang, H.-C., Zhang, Z., and Liu, G. (2008) 'Effect of Yb, Cr and Zr additions on recrystallization and corrosion resistance of Al-Zn-Mg-Cu alloys', *Materials Science and Engineering: A*, 497(1-2), 426-431.
- Chen, S., Chen, K., Peng, G., Jia, L., and Dong, P. (2012a) 'Effect of heat treatment on strength, exfoliation corrosion and electrochemical behavior of 7085 aluminum alloy', *Materials & Design*, 35, 93-98.
- Chen, S., Li, G. M., Chang, W. S., and Chen, X. Q. (2013a) 'The Research of Electrochemical Behavior of Alloy AA5083 in 3.5% NaCl Solution', *Advanced Materials Research*, 676, 80-84.
- Chen, Y., Hong, L., Wang, L., and Chen, W. (2013b) 'Influence of Homogenization on Mechanical Properties of Al-1Mn-1Mg Alloy Prepared by Different Melt-Treatments', *Open Materials Science Journal*, 7, 33-38.
- Chen, Z., Chen, P., and Li, S. (2012b) 'Effect of Ce addition on microstructure of Al₂₀Cu₂Mn₃ twin phase in an Al-Cu-Mn casting alloy', *Materials Science and Engineering: A*, 532, 606-609.
- Chen, Z., Li, S., Liu, K., and Hihara, L. H. (2015) 'A study on the mechanical property and corrosion sensitivity of an AA5086 friction stir welded joint', <http://arxiv.org/abs/1511.04990>.
- Cheng, X.-H., and Xie, C.-Y. (2003) 'Effect of rare earth elements on the erosion resistance of nitrided 40Cr steel', *Wear*, 254(5-6), 415-420.
- Chernov, V., Kardashev, B., and Moroz, K. (2016) 'Low-temperature embrittlement and fracture of metals with different crystal lattices-Dislocation mechanisms', *Nuclear Materials and Energy*, 9, 496-501.
- Choi, I.-K., Cho, S.-H., Kim, S.-J., Jo, Y.-S., and Kim, S.-H. (2018) 'Improved Corrosion Resistance of 5XXX Aluminum Alloy by Homogenization Heat Treatment', *Coatings*, 8(1), 39.

- Christman, T., and Shewmon, P. G. (1979) 'Erosion of a strong aluminum alloy', *Wear*, 52(1), 57-70.
- Clark, D., Russell, T., and Wood, D. (1961) 'The influence of grain size on the yield phenomenon in steel', *Acta Metallurgica*, 9(12), 1054-1063.
- Cocks, D. (1996) 'A Proposed Simple Qualitative Classification for Die-casting Defects', *Proc. Die-casting Conference*, held 1996 Montreaux, Switzerland, 1-15
- Codaro, E., Nakazato, R., Horovistiz, A., Ribeiro, L., Ribeiro, R., and Hein, L. d. O. (2002). 'An image processing method for morphology characterization and pitting corrosion evaluation', *Materials Science and Engineering: A*, 334(1-2), 298-306.
- Conserva, M., and Leoni, M. (1975) 'Effect of thermal and thermo-mechanical processing on the properties of Al-Mg alloys', *Metallurgical Transactions A*, 6(1), 189-195.
- Craig, B. D., Lane, R. A., and Rose, D. H. (2006). *Corrosion prevention and control: A program management guide for selecting materials*. Advanced Materials, Manufacturing, and Testing Information Analysis Center (AMMTIAC). 2nd Edition, Alion Science and Technology New York. USA, 1-377.
- Cramer, S. D., & Covino, B. S. (2003). *ASM Handbook: Corrosion: fundamentals, testing, and protection*. Vol. 13 A. ASM international. Materials Park, OH: ASM International
DOI:<https://doi.org/10.31399/asm.hb.v13a.9781627081825>
- Cui, Z., Li, X., Xiao, K., Dong, C., Wang, L., Zhang, D., et al. (2015) 'Exfoliation Corrosion Behavior of 2B06 Aluminum Alloy in a Tropical Marine Atmosphere', *Journal of Materials Engineering and Performance*, 24(1), 296-306.
- Cverna, F. (2001). *Worldwide guide to equivalent nonferrous metals and alloys*, 4th edn. ASM International, Metals Park OH, 154-157.
- Czechowski, M. (2005) 'Low-cycle fatigue of friction stir welded Al-Mg alloys', *Journal of Materials Processing Technology*, 164, 1001-1006.
- Czyryca, E. J., and Hack, H. P. (1974) 'Corrosion of aluminum alloys in exfoliation-resistant tempers exposed to marine environments for 2 Years', Report No. 4432, Naval Ship Research and Development Centre, Annapolis, MD, U.S.A.

- Das, S. K. (2006) 'Designing aluminium alloys for a recycling friendly world', *Materials Science Forum*, 519, 1239-1244.
- Daud, A., and Wong, K. M. (2004) 'The effect of cerium additions on dent resistance of Al-0.5 Mg-1.2 Si-0.25 Fe alloy for automotive body sheets', *Materials Letters*, 58(20), 2545-2547.
- Davis, J. R. (1993). *Aluminum and aluminum alloys*, 1st edn, Materials Park, OH, ASM International, 133-145.
- Davis, J. R. (1999). *Corrosion of aluminum and aluminum alloys*, 2nd edn. ASM International, USA, 25-49.
- Davis, J. R. (2000). *Corrosion: Understanding the basics*, 1st edn. ASM International, Materials Park, OH, USA, 33-98.
- Davoodi, A., Esfahani, Z., and Sarvghad, M. (2016) 'Microstructure and corrosion characterization of the interfacial region in dissimilar friction stir welded AA5083 to AA7023', *Corrosion Science*, 107, 133-144.
- DELICI, V. P. E. S. T. (2014) 'The effect of heat treatments on the solid-particle erosion behavior of the Aluminum alloy AA2014', *Materiali in Tehnologije*, 48(1), 141-147.
- Devaiah, K., and Laxminarayana (2016) 'Study the process parametric influence on impact strength of friction stir welding of dissimilar aluminum alloys (AA5083 and AA6061) using taguchi technique', *International Advanced Research Journal in Science, Engineering and Technology (IARJSET)*, 3(10), 91-98.
- Dieter Jr, G. E. (1976). *Mechanical Metallurgy, Metallurgy and Metallurgical Engineering Series*, 2nd edn. McGraw-Hill, New York. USA, 1-379.
- Dif, R., Warner, T., and Raynaud, G. (1998) 'Corrosion resistance of aluminium-magnesium alloys for the marine market', *Journal of Japan Institute of Light Metals*, 3, 1615-1620.
- Dons, A., Li, Y., and Marioara, C. (2004) 'Precipitation and dissolution of Mn-rich dispersoids during the heating of AA3xxx alloys', *Aluminium*, 80(6), 583-587.
- Dons, A. L. (2001) 'The Alstruc homogenization model for industrial aluminum alloys', *Journal of Light Metals*, 1(2), 133-149.
- Drits, M., Toropova, L., and Bykov, Y. G. (1980) 'Effect of REM on the mechanical properties of aluminum alloys containing 6.5% Mg', *Metal Science and Heat Treatment*, 22(10), 743-745.

- Du, J., Ding, D., Xu, Z., Zhang, J., Zhang, W., Gao, Y., et al. (2017) 'Effect of CeLa addition on the microstructures and mechanical properties of Al-Cu-Mn-Mg-Fe alloy', *Materials Characterization*, 123, 42-50.
- Du, J., Ding, D., Zhang, W., Xu, Z., Gao, Y., Chen, G., et al. (2018) 'Effect of Ce addition on the microstructure and properties of Al-Cu-Mn-Mg-Fe lithium battery shell alloy', *Materials Characterization*, 142, 252-260.
- Easton, M., and StJohn, D. (1999) 'Grain refinement of aluminum alloys: Part II. Confirmation of, and a mechanism for, the solute paradigm', *Metallurgical and Materials Transactions A*, 30(6), 1625-1633.
- Easton, M., and StJohn, D. (2016) 'The effect of alloy content on the grain refinement of aluminium alloys', *Essential Readings in Light Metals*, 3, 393-399.
- Eckermann, F., Suter, T., Uggowitzer, P. J., Afseth, A., and Schmutz, P. (2008) 'The influence of MgSi particle reactivity and dissolution processes on corrosion in Al-Mg-Si alloys', *Electrochimica Acta*, 54(2), 844-855.
- Einav, I., Ewert, U., Herelli, M., Marshall, D., Abd Ibrahim, N., and Shipp, P. (2005). Non-destructive testing for plant life assessment, training course series no. TCS-26. International atomic energy agency, IAEA, Vienna, Austria, 1-61.
- Eivani, A. R., Zhou, J., and Duszcyk, J. (2011) 'Microstructural Evolution During the Homogenization of Al-Zn-Mg Aluminum Alloys', *Recent Trends in Processing and Degradation of Aluminium Alloys*, 477-515.
- El-Amoush, A. S. (2011) 'Intergranular corrosion behavior of the 7075-T6 aluminum alloy under different annealing conditions', *Materials Chemistry and Physics*, 126(3), 607-613.
- Elgallad, E. M., Doty, H. W., Alkahtani, S. A., and Samuel, F. H. (2016) 'Effects of La and Ce addition on the modification of Al-Si based alloys', *Advances in Materials Science and Engineering*, 2016, 1-13.
- Elsabree, I. A. H. (2015) 'Erosion corrosion behavior of metal matrix composites', *International Journal of Modern Sciences and Engineering Technology (IJMSET)*, 2(4), 6-13.
- Embury, J., Lloyd, D., and Ramachandran, T. (1989) 'Strengthening mechanisms in aluminum alloys', *Treatise on Materials Science & Technology*, 31, 579-601.

- Engler, O., Hentschel, T., and Brinkman, H. (2015) 'Correlation of Texture and Intergranular Corrosion in Al-Mg 5xxx series Alloys', *IOP Conference Series: Materials Science and Engineering, Volume 82, 17th International Conference on Textures of Materials (ICOTOM 17) 24–29 August 2014, Dresden, Germany*.1-6
- Engler, O., Liu, Z., and Kuhnke, K. (2013) 'Impact of homogenization on particles in the Al–Mg–Mn alloy AA 5454–Experiment and simulation', *Journal of Alloys and Compounds*, 560, 111-122.
- Engler, O., and Miller-Jupp, S. (2016) 'Control of second-phase particles in the Al–Mg–Mn alloy AA 5083', *Journal of Alloys and Compounds*, 689, 998-1010.
- Erfan, O., El-Nasr, A., BA, A., and Al-mufadi, F. (2014) 'Erosion-corrosion behavior of AA 6066 aluminum alloy', *International Journal of Mechanical Engineering IJME*, 3(1), 15-24.
- Eskin, D. G. (2017) 'Overview of ultrasonic degassing development', *Light Metals*, 1437-1443.
- Ezuber, H., El-Houd, A., and El-Shawesh, F. (2008) 'A study on the corrosion behavior of aluminum alloys in seawater', *Materials & Design*, 29(4), 801-805.
- Fang, D., Bi, G., Jiang, J., Peng, Q., Jiang, Z., Zhang, X., et al. (2013) 'Influences of Y and Y-Rich mischmetal additions on microstructure and compressive properties of As-Cast Al-Mg-Mn Alloy', *Journal of Materials Engineering and Performance*, 22(4), 1201-1207.
- Fang, H., Chao, H., and Chen, K. (2014) 'Effect of Zr, Er and Cr additions on microstructures and properties of Al–Zn–Mg–Cu alloys', *Materials Science and Engineering: A*, 610, 10-16.
- Fang, H., Chen, K., Chen, X., Huang, L., Peng, G., and Huang, B. (2011) 'Effect of Zr, Cr and Pr additions on microstructures and properties of ultra-high strength Al–Zn–Mg–Cu alloys', *Materials Science and Engineering: A*, 528(25-26), 7606-7615.
- Fayomi, O. S. I., Popoola, A. P. I., and Udoye, N. E. (2017) 'Effect of alloying element on the integrity and functionality of aluminium-based alloy', *In Aluminium Alloys-Recent Trends in Processing, Characterization, Mechanical Behavior and Applications: In tech open*, 13, 243-244.

- Féron, D. (2007). *Corrosion behaviour and protection of copper and aluminium alloys in seawater*, Vol. 50, 1st edn. CRC Press, New York, USA, 1-215.
- Field, J., and Hutchings, I. M. (1987). *Surface response to impact. Materials at high strain rates*. 1st edn. Elsevier Applied Science, Essex, England, 243-293.
- Fiorese, E., Bonollo, F., Timelli, G., Arnberg, L., and Gariboldi, E. (2015) 'New classification of defects and imperfections for aluminum alloy castings', *International Journal of Metalcasting*, 9(1), 55-66.
- Flores Ramirez, J. (2006) 'The role of magnesium in the electrochemical behaviour of 5XXX aluminium-magnesium alloys', *Materials Science*, 42(6), 0801-0807.
- Foley, R. (1986) 'Localized corrosion of aluminum alloys-a review', *Corrosion*, 42(5), 277-288.
- Fontana, M. G., and Stactile, W. (1970). *Corrosion Science and Technology*. 1st edn. Plenum Press, London, 1-149.
- Forberg, H. O., Chia, H. E., and Keith, P. S. (1976) 'Process for degassing aluminum and aluminum alloys', USA. Patent No 3,958,981-1976 Washington, DC: U.S. Patent and Trademark Office.
- Frankel, G. (1998) 'Pitting corrosion of metals a review of the critical factors', *Journal of the Electrochemical Society*, 145(6), 2186-2198.
- Frankel, G., Russak, M., Jahnes, C., Mirzamaani, M., and Brusica, V. (1989) 'Pitting of sputtered aluminum alloy thin films', *Journal of the Electrochemical Society*, 136 (4), 1243-1244.
- Frankel, G. S. (2002) 'Localized corrosion phenomenology and controlling parameters', A compilation of special topic reports of the peer review was submitted on February 28, 2002 to U.S. Department of Energy and Bechtel SAIC Company, LLC.
- Friedman, P., and Ghosh, A. (1996) 'Microstructural evolution and superplastic deformation behavior of fine grain 5083Al', *Metallurgical and Materials Transactions A*, 27(12), 3827-3839.
- Fuller, C. B., Krause, A. R., Dunand, D. C., and Seidman, D. N. (2002) 'Microstructure and mechanical properties of a 5754 aluminum alloy modified by Sc and Zr additions', *Materials Science and Engineering: A*, 338(1-2), 8-16.
- García-Bernal, M. A., Hernandez-Silva, D., and Sauce-Rangel, V. (2007) 'Superplastic behavior of coarse-grained Al-Mg-Zn alloys', *Journal of materials science*, 42(11), 3958-3963.

- Gariboldi, E., Bonollo, F., and Rosso, M. (2007) 'Proposal of a classification of defects of high-pressure diecast products', *Metallurgia Italiana*, 99(6), 39.
- Gault, C., Dauger, A., and Boch, P. (1980) 'Decomposition of aluminium-magnesium solid solutions studied by ultrasonic measurements of elastic properties and electron microscopy', *Acta Metallurgica*, 28(1), 51-60.
- Gehring Jr, G, JR. (1979) 'Corrosion of aluminum alloys in high velocity seawater', Report CODE-471, November 1979. Department of the navy office of naval research c1 metallurgy program, USA, 1-47.
- Gehring Jr, G. A., and Peterson, M. (1981) 'Corrosion of 5456-H117 aluminum in high velocity sea water', *Corrosion*, 37(4), 232-242.
- George E. Dieter, J. (1961). *Mechanical Metallurgy*. 1st edn. McGraw Hill Book Company. New York. USA, 1-77.
- Ghali, E. (2010). *Corrosion resistance of aluminum and magnesium alloys: understanding, performance, and testing* (Vol. 12). 1st edn. John Wiley & Sons, 77-101.
- Godard, H. P. (1967). *The corrosion of light metals*. 1st edn. John Wiley & Sons Inc. New York. USA, 1-273.
- Goswami, R., Spanos, G., Pao, P., and Holtz, R. (2010) 'Precipitation behavior of the β phase in Al-5083', *Materials Science and Engineering: A*, 527(4-5), 1089-1095.
- Goswami, R., Spanos, G., Pao, P., and Holtz, R. (2011) 'Microstructural evolution and stress corrosion cracking behavior of Al-5083', *Metallurgical and Materials Transactions A*, 42(2), 348-355.
- Gou, J., Wang, Y., Wang, C., Chu, R., and Liu, S. (2017) 'Effect of rare earth oxide nano-additives on micro-mechanical properties and erosion behavior of Fe-Cr-CB hardfacing alloys', *Journal of Alloys and Compounds*, 691, 800-810.
- Govindaraju, H. K., Jayaraj, T., Sadanandarao, P., and Venkatesha, C. (2010) 'Evaluation of mechanical properties of as-cast Al-Zn-Ce alloy', *Materials & Design*, 31, S24-S29.
- Grandfield, J., and McGlade, P. (1996) 'DC casting of aluminium: process behaviour and technology', *Materials Forum*, 20, 29-51.

- Grasso, V. B. (2013) 'Rare earth elements in national defense: Background, oversight issues, and options for Congress', Report documentation, Form approved OMB No. 0704-0188, Congressional Research Service, The Library of Congress, 101 Independence Ave, SE, Washington, USA, 1-40.
- Grzybowska, A., and Braszczyńska-Malik, K. (2012) 'Microstructural characterization of the As-cast AZ91 magnesium alloy with rare earth elements', *Archives of Foundry Engineering*, 12, 23-26.
- Gschneidner Jr, K. (1980). Preparation and purification of rare earth metals and effect of impurities on their properties. In science and technology of rare earth materials. Academic Press, Inc. New York, USA, 25-47.
- Gschneidner, K. A., Eyring, L., and Lander, G. H. (2002). *Handbook on the physics and chemistry of rare earths* (Vol. 32): Elsevier science B.V. North Holland, Amsterdam, 1-28.
- Guan, R.-G., and Tie, D. (2017) 'A review on grain refinement of aluminum alloys: progresses, challenges and prospects', *Acta Metallurgica Sinica (English Letters)*, 30(5), 409-432.
- Gubicza, J., Chinh, N. Q., Horita, Z., and Langdon, T. (2004a) 'Effect of Mg addition on microstructure and mechanical properties of aluminum', *Materials Science and Engineering: A*, 387, 55-59.
- Gubicza, J., Kassem, M., Ribárik, G., and Ungár, T. (2004b) 'The microstructure of mechanically alloyed Al-Mg determined by X-ray diffraction peak profile analysis', *Materials Science and Engineering: A*, 372(1-2), 115-122.
- Gudić, S., Radošević, J., Krpan-Lisica, D., and Kliškić, M. (2001) 'Anodic film growth on aluminium and Al-Sn alloys in borate buffer solutions', *Electrochimica Acta*, 46(16), 2515-2526.
- Gudić, S., Radošević, J., Smoljko, I., and Kliškić, M. (2005) 'Cathodic breakdown of anodic oxide film on Al and Al-Sn alloys in NaCl solution', *Electrochimica Acta*, 50(28), 5624-5632.
- Guillaumin, V., and Mankowski, G. (2000) 'Localized corrosion of 6056 T6 aluminium alloy in chloride media', *Corrosion Science*, 42(1), 105-125.
- Gulden, M. E. (1979). Influence of Brittle to Ductile Transition on Solid Particle Erosion Behavior. Proceedings of 5th International Conference on Erosion by Liquid and Solid Impact, 5th, Cambridge, England, 31-31.

- Gupta, R., Wang, Y., Zhang, R., Sukiman, N., Davies, C., and Birbilis, N. (2012) 'Imparting sensitization resistance to an Al-5Mg alloy via neodymium additions', *Corrosion*, 69(1), 4-8.
- Gupta, R., Zhang, R., Davies, C., and Birbilis, N. (2013) 'Theoretical study of the influence of microalloying on sensitization of AA5083 and moderation of sensitization of a model Al-Mg-Mn Alloy via Sr additions', *Corrosion*, 70(4), 402-413.
- Haboudou, A., Peyre, P., Vannes, A., and Peix, G. (2003) 'Reduction of porosity content generated during Nd: YAG laser welding of A356 and AA5083 aluminium alloys ', *Materials Science and Engineering: A*, 363(1-2), 40-52.
- Hajar, H., Zulkifli, F., Mohd Sabri, M., and Wan Nik, W. (2016) 'Protection against corrosion of aluminum alloy in marine environment by lawsonia inermis', *International Journal of Corrosion*, 1, 1-5.
- Hall, E. (1951) 'The Deformation and Ageing of Mild Steel: III discussion of results', *Proceedings of the Physical Society. Section B*, 64(9), 747.
- Hanawa, T. (2000) 'Corrosion measurements of biomedical metallic materials', *Zairyo-to-Kankyo*, 49(8), 463-468.
- He, L., Li, X., Liu, X., Wang, X., Zhang, H., and Cui, J. (2010) 'Effects of homogenization on microstructures and properties of a new type Al-Mg-Mn-Zr-Ti-Er alloy', *Materials Science and Engineering: A*, 527(29-30), 7510-7518.
- Herling, D. R., and Smith, M. T. (2001) 'Improvements in superplastic performance of commercial AA5083 aluminium processed by equal channel angular extrusion', *Materials Science Forum*, 357, 465-470.
- Hess, J. (1983) 'Physical metallurgy of recycling wrought aluminum alloys', *Metallurgical Transactions A*, 14(2), 323-327.
- Hoepfner, D. W. (1985) 'Pitting corrosion: morphology and characterization', *Framework*, 25, 5-1.
- Hosford, W. F. (2010). *Mechanical behavior of materials*. 1st edn. Cambridge university press, 1-454.
- Hu, J., Ikeda, K., and Murakami, T. (1996) 'Effect of heat treatment after hot-rolling on texture and formability for 5083 alloy sheet', *Japan Institute of Light Metals, Journal*, 46(3), 126-137.

- Huang, C., Wu, Z., Huang, R., Wang, W., and Li, L. (2017). Mechanical properties of AA5083 in different tempers at low temperatures. Paper presented at the IOP Conference Series: Materials Science and Engineering, Volume (279), 9-13 July 2017, Madison, Wisconsin, USA. 012002.
- Huang, Y., Li, Y., Xiao, Z., Liu, Y., Huang, Y., and Ren, X. (2016) 'Effect of homogenization on the corrosion behavior of 5083-H321 aluminum alloy', *Journal of Alloys and Compounds*, 673, 73-79.
- Huskins, E., Cao, B., and Ramesh, K. (2010) 'Strengthening mechanisms in an Al-Mg alloy', *Materials Science and Engineering: A*, 527(6), 1292-1298.
- Hutchings, I., and Winter, R. (1974) 'Particle erosion of ductile metals: a mechanism of material removal', *Wear*, 27(1), 121-128.
- Inagaki, H. (2005) 'Precipitation of the β -phase in Al-Mg alloys', *Zeitschrift für Metallkunde*, 96(1), 45-53.
- Ishimaru, H. (1989) 'Ultimate pressure of the order of 10-13 Torr in an aluminum alloy vacuum chamber', *Journal of Vacuum Science & Technology*, 7(3), 2439-2442.
- Ivošević, Š., Meštrović, R., and Kovač, N. (2018) 'Probabilistic estimates of corrosion rate of fuel tank structures of aging bulk carriers', *International Journal of Naval Architecture and Ocean Engineering*, 11(1), 165-177
- J. Zhang, J. J. Z., and R.L. Zuo. (2015). Microstructure and Mechanical Properties of Micro-Alloying Modified Al-Mg Alloys. International Conference on Power Electronics and Energy Engineering April 19-20, 2015 in Hong Kong, China, 153-159.
- Jadayil, W. A. (2011) 'Studying the effects of varying the pouring rate on the casting defects using nondestructive testing techniques', *Jordan Journal of Mechanical and Industrial Engineering*, 5(6), 521-526.
- Jafari, H., Idris, M. H., and Ourdjini, A. (2011) 'High temperature oxidation of AZ91D magnesium alloy granule during in-situ melting', *Corrosion Science*, 53(2), 655-663.
- Jafarzadeh, K., Shahrabi, T., Hadavi, S., and Hosseini, M. (2009) 'Morphological characterization of AA5083-H321 aluminum alloy corrosion in NaCl solution under hydrodynamic conditions', *Anti-Corrosion Methods and Materials*, 56(1), 35-42.

- James P. Schaffer, A. S., et al. (1999). *The science and design of engineering materials*. 2nd edn. New York: McGraw-Hill. 689-691.
- Jiang, H.-c., Ye, L.-y., Zhang, X.-m., Gang, G., Zhang, P., and Wu, Y.-l. (2013) 'Intermetallic phase evolution of 5059 aluminum alloy during homogenization', *Transactions of Nonferrous Metals Society of China*, 23(12), 3553-3560.
- Jiang, W., Fan, Z., Dai, Y., and Li, C. (2014) 'Effects of rare earth elements addition on microstructures, tensile properties and fractography of A357 alloy', *Materials Science and Engineering: A*, 597, 237-244.
- Jin, L. (2012) *Thermodynamic Modeling of Aluminum-Magnesium-Rare Earth Systems*. PhD Thesis, Motreal University, Canada.
- Jin, L., Kang, Y.-B., Chartrand, P., and Fuerst, C. D. (2011) 'Thermodynamic evaluation and optimization of Al-La, Al-Ce, Al-Pr, Al-Nd and Al-Sm systems using the modified quasichemical model for liquids', *Calphad*, 35(1), 30-41.
- Jo, C., Choi, C.-H., Kim, S., and Hwang, W. S. (2002) 'Effect of velocity on corrosion characteristics of Al-Mg alloys', *Metals and Materials International*, 8(6), 563.
- Johnson, K. (1985). *Contact mechanics*. 1st edn. Cambridge University press London. UK, 365.
- Jones, D. (1996a). *Principles and prevention of corrosion*. 2nd edn. Englewood Cliffs: NJ: Prentice-Hall. Inc. USA, 177-169.
- Jones, D. A. (1996b). *Principles and prevention of corrosion*. 2nd edn. Englewood Cliffs: NJ: Prentice-Hall. Inc. USA, 168-198.
- Jones, R., Baer, D., Danielson, M., and Vetrano, J. (2001) 'Role of Mg in the stress corrosion cracking of an Al-Mg alloy', *Metallurgical and Materials Transactions A*, 32(7), 1699-1711.
- Jones, R. H., Gertsman, V. Y., Vetrano, J. S., and Windisch Jr, C. (2004) 'Crack-particle interactions during intergranular stress corrosion of AA5083 as observed by cross-section transmission electron microscopy', *Scripta Materialia*, 50(10), 1355-1359.
- Jordens, A., Cheng, Y. P., and Waters, K. E. (2013) 'A review of the beneficiation of rare earth element bearing minerals', *Minerals Engineering*, 41, 97-114.

- Joshi, A., and Jugulkar, L. (2014) 'Investigation and analysis of metal casting defects and defect reduction by using quality control tools', *International Journal of Mechanical and Production Engineering*, 2(4), 87-92.
- Jurczak, W. (2016) 'Study of the corrosion resistance of ship aluminium alloys', *Scientific Journal of Polish Naval Academy*, 206(3), 37-65.
- Takeuchi, I., Long, C., Famodu, O., Murakami, M., Hattrick-Simpers, J., Rubloff, G., et al. (2005) 'Data management and visualization of x-ray diffraction spectra from thin film ternary composition spreads', *Review of Scientific Instruments*, 76(6), 062223.
- Kaibyshev, R., Musin, F., Lesuer, D., and Nieh, T. (2003) 'Superplastic behavior of an Al-Mg alloy at elevated temperatures', *Materials Science and Engineering: A*, 342(1-2), 169-177.
- Kaiser, M., Datta, S., Roychowdhury, A., and Banerjee, M. (2008a) 'Effect of scandium additions on the tensile properties of cast Al-6Mg alloys', *Journal of Materials Engineering and Performance*, 17(6), 902.
- Kaiser, M., Datta, S., Roychowdhury, A., and Banerjee, M. (2008b) 'Effect of scandium on the microstructure and ageing behaviour of cast Al-6Mg alloy', *Materials Characterization*, 59(11), 1661-1666.
- Kaiser, M., and Dutta, S. (2014) 'Corrosion Behaviour of Aluminium Engine Block in 3.5% NaCl Solution', *Journal of Materials Science and Chemical Engineering*, 2(10), 52.
- Kashyap, K., and Chandrashekar, T. (2001) 'Effects and mechanisms of grain refinement in aluminium alloys', *Bulletin of Materials Science*, 24(4), 345-353.
- Kaufman, J. G. (2000). *Introduction to aluminum alloys and tempers*. 1st edn. ASM international, Materials Park, Ohio, USA, 1-7.
- Kaufman, J. G. (2001). *Fracture resistance of aluminum alloys: Notch toughness, tear resistance, and fracture toughness*. 1st edn. ASM international, Materials Park, Ohio, USA, 111-123.
- Kaufman, J. G., and Rooy, E. L. (2004). *Aluminum alloy castings: properties, processes, and applications*. 1st edn. ASM international, Materials Park, Ohio, USA, 71-77
- Kearsley, A. T., Burchell, M. J., Hörz, F., Cole, M. J., and Schwandt, C. S. (2006) 'Laboratory simulation of impacts on aluminum foils of the Stardust

- spacecraft: Calibration of dust particle size from comet Wild-2', *Meteoritics & Planetary Science*, 41(2), 167-180.
- Keiser, J., Heidersbach, R., Dobbs, D., and Oliver, W. (1988a) 'Response of aluminum alloys to erosive particle impacts', *Journal of Materials Engineering*, 10(4), 273-279.
- Keiser, J. R., Heidersbach, R. S., Dobbs Jr, D. L., and Oliver, W. C. (1988b) 'Characteristics of individual impact craters on selected aluminum alloys', *Wear*, 124(1), 105-118.
- Kelly, R. G., Scully, J. R., Shoesmith, D., and Buchheit, R. G. (2002). *Electrochemical techniques in corrosion science and engineering: Marcel Dekker, Inc., New York, USA,*
- Kendig, K., and Miracle, D. (2002) 'Strengthening mechanisms of an Al-Mg-Sc-Zr alloy', *Acta Materialia*, 50(16), 4165-4175.
- Kenneth G. Budinski, a. M. K. B. (2010). *Engineering materials: Properties and selection*. 9th edn. Prentice Hall: Reston, VA, USA, 37-77.
- Khamaj, J. A. (2015a) 'Comparison of potentiodynamic polarization and weight Loss measurement techniques in the study of corrosion behavior of 6061 Al/SiC composite in 3.5 M NaCl solution', *Asian Journal of Applied Sciences*, 03(02), 264-270.
- Khamaj, J. A. (2015b) 'Comparison of potentiodynamic polarization and weight loss measurement techniques in the study of corrosion behavior of 6061 Al/SiC composite in 3.5 M NaCl solution', *Asian Journal of Applied Sciences*, 03(02), 264-270.
- Khan, M. I., and Yasmin, T. (2014) 'Erosion corrosion of low carbon (AISI 1008 Steel) ring gasket under dynamic high-pressure CO₂ environment', *Journal of Failure Analysis and Prevention*, 14(4), 537-548.
- Kissell, J. R., and Ferry, R. L. (2002). *Aluminum structures: a guide to their specifications and design*. 1st edn. John Wiley & Sons. New York. USA, 32-33.
- Kohlhöfe, W., and Penny, R. (1995) 'Dynamic hardness testing of metals', *International Journal of Pressure Vessels and Piping*, 61(1), 65-75.
- Kora T Sunny, Joseph, J., Georgekutty, S. M., And Mathew, J. (2013) 'A review on mechanical & microstructural property evaluation of aluminium 5083 alloy weldment', *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)*, 3(4), 119-128.

- Kosa, E., and Göksenli, A. (2018) 'Influence of material hardness and particle velocity on erosive wear rate', *Journal of Mechanical Engineering*, 47(1), 9-15.
- Kubiak, A. D. (2009) *Effect of Homogenization on High Temperature Deformation Behaviour of AA3xxx Aluminum Alloys*. PhD Thesis, University of British Columbia.
- Lai, J.P., Jiang, R.-p., Liu, H.-s., Dun, X.-l., Li, Y.-f., and Li, X.-q. (2012) 'Influence of cerium on microstructures and mechanical properties of Al-Zn-Mg-Cu alloys', *Journal of Central South University*, 19(4), 869-874.
- Lathabai, S., and Lloyd, P. (2002) 'The effect of scandium on the microstructure, mechanical properties and weldability of a cast Al-Mg alloy', *Acta Materialia*, 50(17), 4275-4292.
- Leng, Y. (2009a). *Materials characterization: introduction to microscopic and spectroscopic methods*. 2nd edn. John Wiley & Sons. (Asia) Pte Ltd, Singapore. 111-125
- Leng, Y. (2009b). *Materials characterization: introduction to microscopic and spectroscopic methods*. 2nd edn. John Wiley & Sons. (Asia) Pte Ltd, Singapore. 79-109.
- Levy, A. V. (1981) 'The solid particle erosion behavior of steel as a function of microstructure', *Wear*, 68(3), 269-287.
- Levy, A. V. (1986) 'The platelet mechanism of erosion of ductile metals', *Wear*, 108(1), 1-21.
- Levy, A. V. (1995). *Solid particle erosion and erosion-corrosion of materials*. 1st edn. ASM International. Materials Park, Ohio, USA, 149-155.
- Levy, A. V. (1978). The effects of the microstructure of ductile alloys on solid particle erosion behaviour. Report. Prepared at the 1978 for the U.S. Department of Energy under Contract W-7405-ENG-48. Lawrence Berkeley National Laboratory, USA. Permalink. At; <https://escholarship.org/uc/item/64g815n6>
- Levy, A. V., and Jahanmir, S. (1978). The effects of the microstructure of ductile alloys on solid particle erosion behavior. Report. Prepared at the 1978 for the U.S. Department of energy under contract W-7405-ENG-48. Lawrence Berkeley National Laboratory, USA. Permalink <https://escholarship.org/uc/item/64g815n6>

- Li, B., Pan, Q., Huang, X., and Yin, Z. (2014) 'Microstructures and properties of Al–Zn–Mg–Mn alloy with trace amounts of Sc and Zr', *Materials Science and Engineering: A*, 616, 219-228.
- Li, H., Wang, H., Liang, X., Wang, Y., and Liu, H. (2012a) 'Effect of Sc and Nd on the microstructure and mechanical properties of Al-Mg-Mn alloy', *Journal of Materials Engineering and Performance*, 21(1), 83-88.
- Li, Y., and Arnberg, L. (2004) Phase Selection and Phase Transformation in Eutectic Iron- bearing Particles in a DC-Cast AA5182 Alloy. The 9th International Conference on Aluminium Alloys (ICAA9). 2-5 August 2004, Brisbane, Australia, 998.
- Li, Y., and Arnberg, L. (2003) 'Quantitative study on the precipitation behavior of dispersoids in DC-cast AA3003 alloy during heating and homogenization', *Acta Materialia*, 51(12), 3415-3428.
- Li, Y., Hung, Y., Du, Z., Xiao, Z., and Jia, G. (2018) 'The effect of homogenization on the corrosion behavior of Al-Mg Alloy', *Physics of Metals and Metallography*, 119(4), 339-346.
- Li, Y., Liu, Z., Xia, Q., and Liu, Y. (2007) 'Grain refinement of the Al-Cu-Mg-Ag alloy with Er and Sc additions', *Metallurgical and Materials Transactions A*, 38(11), 2853-2858.
- Li, Y., Yang, Y., Wu, Y., Wang, L., and Liu, X. (2010) 'Quantitative comparison of three Ni-containing phases to the elevated-temperature properties of Al-Si piston alloys', *Materials Science and Engineering: A*, 527(26), 7132-7137.
- Li, Y., Zhang, W., and Marthinsen, K. (2012b) 'Precipitation crystallography of plate-shaped Al₆ (Mn, Fe) dispersoids in AA5182 alloy', *Acta Materialia*, 60(17), 5963-5974.
- Lian, J., Garay, J. E., and Wang, J. (2007) 'Grain size and grain boundary effects on the mechanical behavior of fully stabilized zirconia investigated by nanoindentation', *Scripta Materialia*, 56(12), 1095-1098.
- Liang, N., Zhao, Y., Wang, J., and Zhu, Y. (2017) 'Effect of grain structure on Charpy impact behavior of copper', *Scientific Reports*, 7: 44783, 1-11
- Liao, J., Hotta, M., Kaneko, K., and Kondoh, K. (2009) 'Enhanced impact toughness of magnesium alloy by grain refinement', *Scripta Materialia*, 61(2), 208-211.

- Lim, M. L. C., Kelly, R. G., and Scully, J. R. (2015) ‘Overview of intergranular corrosion mechanisms, phenomenological observations, and modeling of AA5083’, *Corrosion*, 72(2), 198-220.
- Li Jin-feng, Zhang Zhao, Cao Fa-he, Cheng Ymg-liang, Zhang Jim-qing, (2003) ‘Investigation of exfoliation corrosion of rolled AA8090 Al-Li alloy using electrochemical impedance spectroscopy. *Trans Nonferrous Met Soc China*, 13(2), 320-324.
- Lim, Y. P., and Yeo, W. H. (2015). Effect of yttrium on the microstructure of gravity die cast A356 Alloy. Paper presented at the Proceedings of the World Congress on Mechanical, Chemical, and Material Engineering, July 20-21, 2015 Barcelona, Spain, 123-130.
- Liu, T., Robinson, J., and McCarthy, M. (2004) ‘The influence of hot deformation on the exfoliation corrosion behaviour of aluminium alloy AA2025’, *Journal of Materials Processing Technology*, 153, 185-192.
- Liu, Y., and Cheng, Y. (2011) ‘Inhibition of corrosion of 3003 Aluminum alloy in ethylene glycol-water solutions’, *Journal of Materials Engineering and Performance*, 20(2), 271-275.
- Liu, Y., Huang, G., Sun, Y., Zhang, L., Huang, Z., Wang, J., et al. (2016a) ‘Effect of Mn and Fe on the formation of Fe-and Mn-rich intermetallics in Al–5Mg–Mn alloys solidified under near-rapid cooling’, *Materials*, 9(2), 88.
- Liu, Y., Luo, L., Han, C., Ou, L., Wang, J., and Liu, C. (2016b) ‘Effect of Fe, Si and cooling rate on the formation of Fe-and Mn-rich intermetallics in Al–5Mg–0.8 Mn alloy’, *Journal of Materials Science & Technology*, 32(4), 305-312.
- Liu, Y., Ou, L., Han, C., Zhang, L., and Zhao, Y. (2016c) ‘The influence of Mn on the microstructure and mechanical properties of the Al–5Mg–Mn alloy solidified under near-rapid cooling’, *Journal of Materials Research*, 31(8), 1153-1162.
- Liu, Y., Sun, Y., Zhang, L., Zhao, Y., Wang, J., and Liu, C. (2017) ‘Microstructure and Mechanical Properties of Al-5Mg-0.8 Mn Alloys with Various Contents of Fe and Si Cast under Near-Rapid Cooling’, *Metals*, 7(10), 428.
- Liu, Z., Liu, X. M., and Hu, Y. M. (2011) ‘Effect of eutectic reaction induced by Pr on microstructure in semisolid A356 alloy’, *Advanced Materials Research*, 322, 361-364.

- Llorca-Isern, N., Luis-Perez, C., Gonzalez, P., Laborde, L., and Patino, D. (2005) 'Analysis of structure and mechanical properties of AA 5083 aluminium alloy processed by ECAE', *Rev. Adv. Mater. Sci*, 10, 473-478.
- Long, J. (1998) 'Nondestructive testing: 5 ways to ensure defect-free deliveries', *Modern Casting (USA)*, 88(4), 49-52.
- Lucadamo, G., Yang, N., San Marchi, C., and Lavernia, E. (2006) 'Microstructure characterization in cryomilled Al 5083', *Materials Science and Engineering: A*, 430(1-2), 230-241.
- Lumley, R. (2010). *Fundamentals of aluminium metallurgy: production, processing and applications*. 1st edn. Woodhead, Cambridge, UK, 177-175.
- Lundi, R., and Wilson, J. (2002). Rare earth metals find interesting new uses despite lack of engineering data. Imperial College Press, Uk, 1-7.
- Mackenzie, G. E. T. a. D. S. (2003). *Handbook of aluminum, physical metallurgy and processes* (Vol. 1). Marcel Dekker, Inc, New York, USA, 77.
- Mahmoud, M., Samuel, A., Doty, H., Valtierra, S., and Samuel, F. (2017) 'Effect of solidification rate and rare earth metal addition on the microstructural characteristics and porosity formation in A356 Alloy', *International Journal of Metal Casting*, 12(2), 251-265.
- Makarov, S., Apelian, D., and Ludwig, R. (1998). Inclusion removal and detection in molten aluminum: mechanical, electromagnetic and acoustic techniques. Paper presented at the One Hundred Third Annual Meeting of the American Foundrymen's Society, 727-735.
- Malina, J., and Radošević, J. (2015) 'Influence of NaCl concentration on pitting corrosion of extruded Al-Mg-Si alloy AA6060', *Zaštita Materijala*, 56(1), 47-51.
- Marc Andr e Meyers, a. K. K. C. (2009). *Mechanical Behavior of Materials*. 2nd edn. Cambridge University Press. UK. 353
- Marc, O. J. (1996) 'Mechanistic model of corrosion pitting on 2024 T3 alloy', *Krzepnięcie Metalu i Stopów*, 28, 226-232.
- Marcus, P. (Ed.). (2011). *Corrosion mechanisms in theory and practice*. 3rd edn. CRC Press. Taylor and Francis Group, LLC. USA.
- Marquis, E. A., Seidman, D. N., Asta, M., and Woodward, C. (2006) 'Composition evolution of nanoscale Al₃Sc precipitates in an Al-Mg-Sc alloy: Experiments and computations', *Acta Materialia*, 54(1), 119-130.

- Mathur, K., Needleman, A., and Tvergaard, V. (1994) '3D analysis of failure modes in the Charpy impact test', *Modelling and Simulation in Materials Science and Engineering*, 2(3A), 617-635.
- Mazurkiewicz, B. (1983) 'The electrochemical behaviour of the Al₈Mg₅ intermetallic compound', *Corrosion Science*, 23(7), 687-696.
- McCabe, L. P., Sargent, G. A., and Conrad, H. (1985) 'Effect of microstructure on the erosion of steel by solid particles', *Wear*, 105(3), 257-277.
- McCartney, D. (1989) 'Grain refining of aluminium and its alloys using inoculants', *International Materials Reviews*, 34(1), 247-260.
- Meng, C., Zhang, D., Cui, H., Zhuang, L., and Zhang, J. (2014) 'Mechanical properties, intergranular corrosion behavior and microstructure of Zn modified Al-Mg alloys', *Journal of Alloys and Compounds*, 617, 925-932.
- Meng, H., and Ludema, K. (1995) 'Wear models and predictive equations: their form and content', *Wear*, 181, 443-457.
- Meng, L., and Zheng, X. (1997) 'Overview of the effects of impurities and rare earth elements in Al-Li alloys. *Materials Science and Engineering*', A, 237(1), 109-118.
- Moldovan, P., Stanica, C. N., Ciobanu, G., Ungureanu, I., Iorga, G. M., and Buțu, M. (2014). 'Intergranular corrosion of AA 5083-H321 aluminum alloy', *UPB Sci Bull Ser B Chem Mater Sci*, 76(3), 169-180.
- Mondolfo, L. F. (2013). *Aluminum alloys: structure and properties*. 1st edn. Butterworths LTD, UK. 806.
- Mouritz, A. P. (2012). *Introduction to aerospace materials*. 1st edn. Cambridge: Woodhead.,Uk, 1-650.
- Muhammad A. Farrukh (2012). *Atomic absorption spectrometry (AAS)*.1st edn. García, R., and Báez, ,A. *Atomic absorption spectrometry (AAS)*. InTech. Croatia, 1, 1-13.
- Murray, J. L. (1982) 'The Al-Mg (aluminum– magnesium) system', *Journal of Phase Equilibria*, 3(1), 60.
- Murty, B., Kori, S., and Chakraborty, M. (2002) 'Grain refinement of aluminium and its alloys by heterogeneous nucleation and alloying', *International Materials Reviews*, 47(1), 3-29.
- Nakamura, M. (1995) 'Fundamental properties of intermetallic compounds', *MRS Bulletin*, 20(8), 33-39.

- Nebti, S., Hamana, D., and Cizeron, G. (1995) 'Calorimetric study of pre-precipitation and precipitation in Al-Mg alloy', *Acta Metallurgica et Materialia*, 43(9), 3583-3588.
- Neville, A., Reyes, M., and Xu, H. (2002) 'Examining corrosion effects and corrosion/erosion interactions on metallic materials in aqueous slurries', *Tribology International*, 35(10), 643-650.
- Nie, Z., Fu, J., Zou, J., Jin, T., Yang, J., Xu, G., et al. (2004) 'Advanced aluminum alloys containing rare-earth erbium', *Materials Forum*, 28, 197-201.
- Nie, Z. R., Jin, T., Fu, J., Xu, G., Yang, J., Zhou, J. X., et al. (2002) 'Research on rare earth in aluminum', *Materials Science Forum*, 396, 1731-1735
- Nie, Z. R., Li, B., Wang, W., Jin, T., Huang, H., Li, H., et al. (2007) 'Study on the erbium strengthened aluminum alloy', *Materials science forum*, 546, 623-628.
- Nieh, T., Hsiung, L., Wadsworth, J., and Kaibyshev, R. (1998) 'High strain rate superplasticity in a continuously recrystallized Al-6% Mg-0.3% Sc alloy', *Acta Materialia*, 46(8), 2789-2800.
- Nis, K. (1990) 'Electrochemical behavior of aluminum-base intermetallics containing iron', *Journal of the Electrochemical Society*, 137(1), 69-77.
- Nisancioglu, K., Lunder, O., and Holtan, H. (1985) 'Improving the corrosion resistance of aluminum alloys by cathodic polarization in aqueous media', *Corrosion*, 41(5), 247-257.
- Oguocha, I., Adigun, O., and Yannacopoulos, S. (2008) 'Effect of sensitization heat treatment on properties of Al-Mg alloy AA5083-H116', *Journal of Materials Science*, 43(12), 4208-4214.
- Oguzie, E. E. (2007) 'Corrosion inhibition of aluminium in acidic and alkaline media by Sansevieria trifasciata extract', *Corrosion Science*, 49(3), 1527-1539.
- Oka, Y. I., Okamura, K., and Yoshida, T. (2005) 'Practical estimation of erosion damage caused by solid particle impact: Part 1: Effects of impact parameters on a predictive equation', *Wear*, 259(1-6), 95-101.
- Omura, N., Murakami, Y., Li, M., Tamura, T., Miwa, K., Furukawa, H., et al. (2009) 'Effects of mechanical vibration on macrostructure and mechanical properties of AC4C aluminum alloy castings', *Materials Transactions*, 50(11), 2578-2583.

- Orłowicz, W., Tupaj, M., Mróz, M., and Guzik, E. (2010) 'Evaluation of ductile iron casting material quality using ultrasonic testing', *Journal of Materials Processing Technology*, 210(11), 1493-1500.
- Ozden, S., Ekici, R., and Nair, F. (2007) 'Investigation of impact behaviour of aluminium based SiC particle reinforced metal-matrix composites', *Composites Part A: Applied Science and Manufacturing*, 38(2), 484-494.
- Parida, N. (1999a) 'Non-destructive testing and evaluation of cast materials', *Materials Characterization Techniques-Principles and Applications*, 177-193.
- Parida, N. (1999b) 'Non-destructive testing and evaluation of cast materials', *Materials Characterization Techniques-Principles and Applications*, 177-193.
- Patakham, U., Kajornchaiyakul, J., and Limmaneevichitr, C. (2012) 'Grain refinement mechanism in an Al-Si-Mg alloy with scandium', *Journal of Alloys and Compounds*, 542, 177-186.
- Patel, P. J., Shah, S. C., and Makwana, S. (2014) 'Application of quality control tools in taper shank drills manufacturing industry: A case study', *International Journal of Engineering Research and Applications*, 4(2), 129-134.
- Pattnaik, A. B., Das, S., Jha, B. B., and Prasanth, N. (2015) 'Effect of Al-5Ti-1B grain refiner on the microstructure, mechanical properties and acoustic emission characteristics of Al5052 aluminium alloy', *Journal of Materials Research and Technology*, 4(2), 171-179.
- Paul, J., & Campbell, G. (2011). Investigating rare earth element, mine development in EPA region 8 and potential environmental impacts. Report on August 15, 2011 EPA Document-908R11003. Environmental Protection Agency USA.
- Peng, J.-H., Li, W.-F., Huang, F.-L., and Jun, D. (2009) 'Effect of rare earth Pr on microstructure and mechanical properties of Al₂O₃-SiO₂ (sf)/Al-Si composites', *Transactions of Nonferrous Metals Society of China*, 19(5), 1081-1086.
- Pérez-Bustamante, R., Reyna-Cruz, A., Acosta-Peña, D., Santillán-Rodríguez, C., Matutes-Aquino, J., Pérez-Bustamante, F., et al. (2016) 'Effect of cerium/lanthanum addition on microstructure and mechanical properties of Al7075 alloy via mechanical alloying and sintering', *Journal of Rare Earths*, 34(4), 420-427.
- Petch, N. J. (1953) 'The cleavage strength of polycrystals', *Journal of the Iron and Steel Inst.*, 174, 25-28.

- Pineau, A., Benzerga, A. A., and Pardoën, T. (2016) 'Failure of metals I: Brittle and ductile fracture', *Acta Materialia*, 107, 424-483.
- Polmear, I. J. (1995). *Metallurgy of the light metals. Light alloys*, 3rd edn. Edward Arnold, London, UK.
- Polmear, I., StJohn, D., Nie, J.-F., and Qian, M. (2017). *Light alloys: Metallurgy of the light metals*. 5th edn. Butterworth-Heinemann is an imprint of Elsevier.
- Popescu, G., Gheorghe, I., Dănilă, F., and Moldovan, P. (1996) 'Vacuum degassing of aluminium alloys', *Materials Science Forum*, 147-152.
- Popović, M., and Romhanji, E. (2002) 'Stress corrosion cracking susceptibility of Al-Mg alloy sheet with high Mg content', *Journal of Materials Processing Technology*, 125, 275-280.
- Portnoi, V., Rilov, D., Levchenko, V., and Alalykin, A. (2005) 'Superplastic magnalium for increased rates of superplastic forming', *Tsvetnye Metally (Nonferrous Metals)* (1), 84-86.
- Portnoy, V., Rylov, D., Levchenko, V., and Mikhaylovskaya, A. (2013) 'The influence of chromium on the structure and superplasticity of Al-Mg-Mn alloys', *Journal of Alloys and Compounds*, 581, 313-317.
- Prukkanon, W., Srisukhumbowornchai, N., and Limmaneevichitr, C. (2009) 'Influence of Sc modification on the fluidity of an A356 aluminum alloy', *Journal of Alloys and Compounds*, 487(1-2), 453-457.
- Ramachandran, T., Sharma, P., and Balasubramanian, K. (2008). Grain Refinement of Light Alloys. In: proceedings of 68th WFC-World Foundry Congress, 7th - 10th February, 2008, Chennai, India, 189-193.
- Ramgopal, T., Gouma, P., and Frankel, G. (2002) 'Role of grain-boundary precipitates and solute-depleted zone on the intergranular corrosion of aluminum alloy 7150', *Corrosion*, 58(8), 687-697.
- Rana, R., Purohit, R., and Das, S. (2012) 'Reviews on the influences of alloying elements on the microstructure and mechanical properties of aluminum alloys and aluminum alloy composites', *International Journal of Scientific and Research Publications*, 2(6), 1-7.
- Rao, M., & Keiser, J. R. (1992). Studies of near-surface phenomena and erosion mechanisms in metallic alloys using single-and multi-particle impacts. Report (No. ORNL/TM-11946) Prepared for the U.S. Department of Energy Office of

Fossil Energy Advanced Research and Technology Development Materials Program.

- Rao, P. V., and Buckley, D. (1985) 'Characterization of solid particle erosion resistance of ductile metals based on their properties', *Journal of Engineering for Gas Turbines and Power*, 107(3), 669-678.
- Rathod, N., and Manghani, J. (2012) 'Effect of modifier and grain refiner on cast Al-7Si aluminum alloy: A review', *International Journal of Emerging Trends in Engineering and Development*, 5(2), 574-582.
- Reboul, M., and Baroux, B. (2011) 'Metallurgical aspects of corrosion resistance of aluminium alloys', *Materials and Corrosion*, 62(3), 215-233.
- Reddy, N., Rao, A. P., Chakraborty, M., and Murty, B. (2005) 'Prediction of grain size of Al-7Si Alloy by neural networks', *Materials Science and Engineering: A*, 391(1-2), 131-140.
- Ribárik, G., Gubicza, J., and Ungár, T. (2004) 'Correlation between strength and microstructure of ball-milled Al-Mg alloys determined by X-ray diffraction', *Materials Science and Engineering: A*, 387, 343-347.
- Rickerby, D., Bai, B. P., and Macmillan, N. (1979) 'The effect of crystallographic orientation on damage in MgO due to spherical particle impact', *Journal of Materials Science*, 14(8), 1807-1816.
- Rinderer, B. (2011) 'The metallurgy of homogenisation', *Materials Science Forum*, 693, 264-275.
- Robinson, M., and Jackson, N. (1999) 'The influence of grain structure and intergranular corrosion rate on exfoliation and stress corrosion cracking of high strength Al-Cu-Mg alloys', *Corrosion Science*, 41(5), 1013-1028.
- Roder, O., Wirtz, T., Gysler, A., and Lütjering, G. (1997) 'Fatigue properties of Al-Mg alloys with and without scandium', *Materials Science and Engineering: A*, 234, 181-184.
- Romhanji, E., and Popović, M. (2006) 'Problems and prospect of Al-Mg alloys application in marine constructions', *Metallurgija*, 12(4), 297-307.
- Rosalbino, F., Angelini, E., De Negri, S., Saccone, A., and Delfino, S. (2003) 'Influence of the rare earth content on the electrochemical behaviour of Al-Mg-Er alloys', *Intermetallics*, 11(5), 435-441.
- Røyset, J., and Ryum, N. (2005) 'Scandium in aluminium alloys', *International Materials Reviews*, 50(1), 19-44.

- Ruff, A. W., & Wiederhorn, S. M. (1979). Erosion by solid particle impact. Report No. NBSIR-78-1575. National Measurement Laboratory Centre for Materials Science. National Bureau of Standards Prepared for the Office of Naval Research Department of the Navy Arlington. Virginia.
- Ryen, Ø., Holmedal, B., Nijs, O., Nes, E., Sjölander, E., and Ekström, H.-E. (2006). ‘Strengthening mechanisms in solid solution aluminum alloys’, *Metallurgical and Materials Transactions A*, 37(6), 1999-2006.
- Safri, S., Sultan, M., Yidris, N., and Mustapha, F. (2014) ‘Low velocity and high velocity impact test on composite materials—a review’, *International Journal of Engineering and Science*, 3(9), 50-60.
- Samaras, S., and Haidemenopoulos, G. (2007) ‘Modelling of microsegregation and homogenization of 6061 extrudable Al-alloy’, *Journal of Materials Processing Technology*, 194(1-3), 63-73.
- Sampath H P, M. S. V., and Veeresh Naik. (2017) ‘Design and fabrication of erosion-corrosion testing machine’, *International Journal of Innovative Research in Advanced Engineering (IJIRAE)* 4(4), 40-48.
- Sanders Jr, R., Hollinshead, P., and Simielli, E. (2004). Industrial development of non-heat treatable aluminum alloys’, *Materials Forum*, 53-64.
- Sawtell, R. R., and Jensen, C. L. (1990) ‘Mechanical properties and microstructures of Al-Mg-Sc alloys’, *Metallurgical Transactions A*, 21(1), 421-430.
- Schmerr, L.W. (2016) *An ultrasonic system. Fundamentals of ultrasonic non-destructive Evaluation*. 2nd edn. Springer, Cham, 1-13.
- Scudino, S., Sperling, S., Sakaliyska, M., Thomas, C., Feuerbacher, M., Kim, K., et al. (2008). ‘Phase transformations in mechanically milled and annealed single-phase β -Al₃Mg₂’, *Acta Materialia*, 56(5), 1136-1143.
- Scully, J., Young, G., and Smith, S. (2012). Hydrogen embrittlement of aluminum and aluminum-based alloys. Gaseous hydrogen embrittlement of materials in energy technologies Volume 2, Woodhead Publishing Series in Metals and Surface Engineering, 707-768.
- Searles, J., Gouma, P., and Buchheit, R. (2001) ‘Stress corrosion cracking of sensitized AA5083 (Al-4.5 Mg-1.0 Mn)’, *Metallurgical and Materials Transactions A*, 32(11), 2859-2867.

- Seman, A. A., and Daud, A. R. (2008) 'The Effect of cerium addition on the microstructure of AlSiMgCe Alloy', *Solid State Science and Technology*, 16(1), 168-174.
- Seniw, M. E., Conley, J. G., and Fine, M. E. (2000) 'The effect of microscopic inclusion locations and silicon segregation on fatigue lifetimes of aluminum alloy A356 castings', *Materials Science and Engineering: A*, 285(1-2), 43-48.
- Seong, J. (2015) *Inhibition of Corrosion and Stress Corrosion Cracking of Sensitized AA5083*. PhD Thesis, Ohio State University, USA.
- Seong, J., Frankel, G., and Sridhar, N. (2014) 'Influence of altered surface layer on corrosion inhibition of AA5083', *Journal of Electrochemical Society*, 162 (6), 209-218.
- Seong, J., Yang, F., Scheltens, F., Frankel, G., and Sridhar, N. (2015) 'Influence of the altered surface layer on the corrosion of AA5083', *Journal of The Electrochemical Society*, 162(6), C209-C218.
- Shabestari, S. (2004) 'The effect of iron and manganese on the formation of intermetallic compounds in aluminium-silicon alloys', *Materials Science and Engineering: A*, 383(2), 289-298.
- Shaw, A., Tian, L., and Russell, A. M. (2016) 'Tensile Properties of High-purity Ca Metal', *British Journal of Applied Science & Technology*, 15(6), 1-6.
- Shaw, B., Davis, G., Fritz, T., Rees, B., and Moshier, W. (1991) 'The influence of tungsten alloying additions on the passivity of aluminum', *Journal of the Electrochemical Society*, 138(11), 3288-3295.
- Sheldon, G. (1977) 'Effects of surface hardness and other material properties on erosive wear of metals by solid particles', *Journal of Engineering Materials and Technology*, 99(2), 133-137.
- Sheldon, G., and Kanhere, A. (1972) 'An investigation of impingement erosion using single particles', *Wear*, 21(1), 195-209.
- Shen, H., Liang, H., Yao, G. C., Yang, W. D., and Ren, X. D. (2012) 'Effect of cerium-rich mischmetal content on the mechanical properties and fracture morphology of new 5XXX series aluminum alloys', *Applied Mechanics and Materials*, 152, 239-243.
- Sheppard, T. (2013) *Extrusion of aluminium alloys*. 3rd edn. Springer Science & Business Media, B.V, 27-77.

- Sheppard, T., and Raghunathan, N. (1989) 'Modification of cast structures in Al-Mg alloys by thermal treatments', *Materials Science and Technology*, 5(3), 268-280.
- Sherif, E., and Almajid, A. A. (2011) 'Corrosion of magnesium/manganese alloy in chloride solutions and its inhibition by 5-(3-aminophenyl)-tetrazole', *Int. J. Electrochem. Sci*, 6, 2131-2148.
- Shih, T.-S., and Wen, K.-Y. (2005) 'Effects of degassing and fluxing on the quality of Al-7% Si and A356. 2 alloys', *Materials Transactions*, 46(2), 263-271.
- Shih, T.-S., and Weng, K.-Y. (2004) 'Effect of a degassing treatment on the quality of Al-7Si and A356 Melts', *Materials Transactions*, 45(6), 1852-1858.
- Sigurd Støren, Trondheim and by Skanaluminium (2101) Understanding Aluminum as a Material, Basic Level, training in aluminum application technologies (TALAT), Lecture 2101.01.
- Skandija, D. (2009) 'Superplasticity of the 5083 aluminium alloy with the addition of scandium', *Materiali in Tehnologije*, 43(6), 299-302.
- Souza, V., and Neville, A. (2007) 'Aspects of microstructure on the synergy and overall material loss of thermal spray coatings in erosion-corrosion environments', *Wear*, 263(1-6), 339-346.
- Speakman, S.A. (2013) Introduction to x-ray powder diffraction data analysis; Technical Report; Center for Materials Science and Engineering at MIT: Cambridge, MA, USA, 19-20.
- Stack, M., Jana, B., and Abdelrahman, S. (2011). Tribocorrosion of passive metals and coatings. 1st edn. *Models and mechanisms of erosion-corrosion in metals* Elsevier, Woodhead Publishing: Cambridge, UK, 153-187.
- Stack, M., Zhou, S., and Newman, R. (1995) 'Identification of transitions in erosion-corrosion regimes in aqueous environments', *Wear*, 186, 523-532.
- Stolyarov, V., Valiev, R., and Zhu, Y. (2006) 'Enhanced low-temperature impact toughness of nanostructured Ti', *Applied Physics Letters*, 88(4), 041905.
- Sukiman, N., Gupta, R., Buchheit, R., and Birbilis, N. (2014a) 'Influence of microalloying additions on Al-Mg alloy. Part 1: Corrosion and electrochemical response', *Corrosion Engineering, Science and Technology*, 49(4), 254-262.
- Sukiman, N., Gupta, R., Zhang, R., Buchheit, R., and Birbilis, N. (2014b) 'Influence of microalloying additions on Al-Mg alloy. Part 2: Phase analysis and

- sensitisation behaviour', *Corrosion Engineering, Science and Technology*, 49(4), 263-268.
- Sukiman, N. L. (2013) 'Imparting sensitization resistance to an Al-5Mg Alloy via neodymium additions', *Corrosion*, 69 (1). 4-8.
- Sun, F., Nash, G. L., Li, Q., Liu, E., He, C., Shi, C., et al. (2017a) 'Effect of Sc and Zr additions on microstructures and corrosion behavior of Al-Cu-Mg-Sc-Zr alloys', *Journal of Materials Science & Technology*, 33(9), 1015-1022.
- Sun, G., Li, Z., Liu, T., Chen, J., Wu, T., and Feng, X. (2017b) 'Rare earth elements in street dust and associated health risk in a municipal industrial base of central China', *Environmental Geochemistry and Health*, 39(6), 1469-1486.
- Sun, Q., Chen, K., Fang, H., Xu, J., Dong, P., Hu, G., et al. (2016) 'Effect of Grain Refinement on Electrochemical Behavior of Al-Zn-Mg-Cu Alloys', *International Journal of Electrochemical Science*, 11, 5855-5869.
- Sundararajan, G., and Roy, M. (1997) 'Solid particle erosion behaviour of metallic materials at room and elevated temperatures ', *Tribology International*, 30(5), 339-359.
- Suter, T., and Alkire, R. C. (2001) 'Micro electrochemical studies of pit initiation at single inclusions in Al 2024-T3. *Journal of the Electrochemical Society*, 148(1), B36-B42.
- Szklarska-Smialowska, Z. (1999) 'Pitting corrosion of aluminum', *Corrosion science*, 41(9), 1743-1767.
- Talib, F., and Ali, M. (2003). Impact of quality circle-Acase study. *Journal of the Institution of Engineers (India)*, 84(5), 10-13.
- Tan, L., and Allen, T. (2010) 'Effect of thermomechanical treatment on the corrosion of AA5083', *Corrosion Science*, 52(2), 548-554.
- Thangaraju, S., Heilmaier, M., Murty, B. S., and Vadlamani, S. S. (2012) 'On the estimation of true Hall-Petch constants and their role on the superposition law exponent in Al alloys', *Advanced Engineering Materials*, 14(10), 892-897.
- The International Organization for Standardization. (1991). *ISO 9916:1991(en)*. American National Standards Institute (ANSI).USA.
- The International Organization for Standardization. (1992). *ISO 10049:1992(en)*. American National Standards Institute (ANSI).USA.
- The International Organization for Standardization. (1992). *ISO 10049:1992(en)*. American National Standards Institute (ANSI).USA.

- The International Organization for Standardization. (1999). *ISO 11881:1999(en)*. American National Standards Institute (ANSI).USA.
- The International Organization for Standardization. (1999). *ISO 8044:2015(en)*. American National Standards Institute (ANSI).USA.
- Tiebao, W., Xiangqian, Q., Xiaodong, W., and Chunyang, L. (2008) ‘Influence of rare earths on structures and properties of 3X04 aluminum alloy ingot’, *Chinese Journal of Rare Metals*, 4, 1-8.
- Tilly, G. (1973) ‘A two stage mechanism of ductile erosion’, *Wear*, 23(1), 87-96.
- Tirupataiah, Y., and Sundararajan, G. (1990) ‘The volume of the crater formed by the impact of a ball against flat target materials-The effect of ball hardness and density’, *International Journal of Impact Engineering*, 9(2), 237-246.
- Topolska, S., and Labanowski, J. (2009) ‘Effect of microstructure on impact toughness of duplex and superduplex stainless steels’, *Journal of Achievements in Materials and Manufacturing Engineering*, 36(2), 142-149.
- Totten, G. E., and MacKenzie, D. S. (2003a). Handbook of aluminum, volume 2: *Alloy production and materials manufacturing*, Marcel Dekker Inc., New York..433-437.
- Totten, G. E., and MacKenzie, D. S. (2003b). Handbook of aluminum, volume 1: *Physical Metallurgy and Processes*, Marcel Dekker Inc., New York, 599-603
- Treseder, R. S. (1991) *NACE corrosion engineer's reference book*. 2nd edn. National Association of Corrosion Engineers, Houston, Texas, USA, 233.
- Treseder, R. S. (1002) *NACE corrosion engineer's reference book*. 3rd edn. National Association of Corrosion Engineers, Houston, Texas, USA, 311.
- Tsai, Y.-C., Chou, C.-Y., Lee, S.-L., Lin, C.-K., Lin, J.-C., and Lim, S. (2009) ‘Effect of trace La addition on the microstructures and mechanical properties of A356 (Al–7Si–0.35 Mg) aluminum alloys’, *Journal of Alloys and Compounds*, 487(1-2), 157-162.
- Tsai, Y.-C., Lee, S.-L., and Lin, C.-K. (2011a) ‘Effect of trace Ce addition on the microstructures and mechanical properties of A356 (Al–7Si–0.35 Mg) aluminum alloys’, *Journal of the Chinese Institute of Engineers*, 34(5), 609-616.
- Tsai, Y. C., Chou, C. Y., Jeng, R. R., Lee, S. L., and Lin, C. K. (2011b) ‘Effect of rare earth elements addition on microstructures and mechanical properties of A356 alloy’, *International Journal of Cast Metals Research*, 24(2), 83-87.

- Uesugi, T., and Higashi, K. (2010) Modeling Solid solution Strengthening Using First-principles Results of Misfit Strain with Friedel Model in Al-based Alloys. In: Proceedings of 12th International Conference on Aluminium Alloys, September 5-9, 2010, Yokohama, Japan, 1421-1425.
- Uhlig, H. H. (2011). Uhlig's corrosion handbook, volume 51. 3rd edn. John Wiley & Sons, Inc. New Jersey, 157-159.
- Umarova, T. (2017) 'Influence of microalloying (Including rare earth metals) on the phase composition and properties of aluminum alloys', *Materials Science Forum*, 890, 331-338.
- Unocic, K. A. (2008) *Structure-Composition-Property Relationships in 5XXX Series Aluminum Alloys*. PhD Thesis, Ohio State University, USA.
- Unocic, K. A., Kobe, P., Mills, M. J., and Daehn, G. S. (2006) 'Grain boundary precipitate modification for improved intergranular corrosion resistance', *Materials science forum*, 519, 327-332.
- Valencia, J. J., & Quested, P. N (2008). ASM Handbook, Volume 15: Casting, ASM International, Materials Park, OH, USA, 416-522.
- V.Neff, D. (2008). ASM Handbook, volume 15, Casting, Degassing, ASM International, Materials Park, Ohio, USA, 185-193.
- Vahdat, N., and Newman, J. (1973) 'Corrosion of an iron rotating disk', *Journal of The Electrochemical Society*, 120(12), 1682-1686.
- Vazirov, N. S., Makhsudova, M., Ganiev, I., and Norova, M. (2013) 'Corrosion-electrochemical properties of Al-Mg-Ce alloy alloyed by cerium', *Izvestiya Akademii Nauk Tadzhikskoj SSR. Otdelenie Fiziko-Matematicheskikh, Khimicheskikh i Geologicheskikh Nauk*, 3(152), 91-97.
- Venkateswarlu, K., Pathak, L., Ray, A. K., Das, G., Verma, P., Kumar, M., et al. (2004) 'Microstructure, tensile strength and wear behaviour of Al-Sc alloy', *Materials Science and Engineering: A*, 383(2), 374-380.
- Verma, R., and Kim, S. (2007) 'Superplastic behavior of copper-modified 5083 aluminum alloy', *Journal of Materials Engineering and performance*, 16(2), 185-191.
- Vetrano, J. S., Williford, R. E., Bruemmer, S. M., and Jones, R. H. (1997) 'Influence of microstructure and thermal history on the corrosion susceptibility of AA 5083', *Minerals, Metals and Materials Society/AIME(USA)*, 77-85.

- Vijayan, V., and Prabhu, K. N. (2016) 'The effect of simultaneous refinement and modification by cerium on microstructure and mechanical properties of Al-8% Si alloy', *International Journal of Cast Metals Research*, 29(6), 345-349.
- Vončina, M., Mrvar, P., Petrič, M., and Medved, J. (2012) 'Microstructure and grain refining performance of Ce on A380 alloy', *Journal of Mining and Metallurgy, Section B: Metallurgy*, 48(2), 265-272.
- Voncken, J. H. L. (2016). Physical and chemical properties of the rare earths. In the rare earth elements, Springer, Cham, 53-72.
- Vander Voort, G. F., & JAMES, H. (2004). ASM Handbook, vol. 9. Metallography and Microstructures, ASM International, OH,USA, 670-700.
- Wang, B., Zhang, L., Su, Y., Xiao, Y., and Liu, J. (2013a) 'Corrosion behavior of 5A05 aluminum alloy in NaCl solution', *Acta Metallurgica Sinica (English Letters)*, 26(5), 581-587.
- Wang, S.-S., Yang, F., and Frankel, G. (2017a) 'Effect of altered surface layer on localized corrosion of aluminum alloy 2024', *Journal of The Electrochemical Society*, 164(6), C317-C323.
- Wang, S., and Bian, X. (2007) 'Crystallization of Al-Mg-Ce and Al-Mg-Ni-Ce amorphous alloys', *Journal of Alloys and Compounds*, 441(1-2), 135-138.
- Wang, S., Zhou, N., Nong, D., and Song, D. (2017b) 'Effects of La and Ce mixed rare earth on microstructure and properties of Al-Mg-Si aluminum alloy', *Materials Science Forum*, 898, 367-371.
- Wang, W.-t., Zhang, X.-m., Gao, Z.-g., Jia, Y.-z., Ye, L.-y., Zheng, D.-w., et al. (2010). 'Influences of Ce addition on the microstructures and mechanical properties of 2519A aluminum alloy plate', *Journal of Alloys and Compounds*, 491(1-2), 366-371.
- Wang, W., and Shuey, R. T. (2010). Homogenization Model for 7xxx Aluminum Alloys Proceedings of the 12th International Conference on Aluminium Alloys, September 5-9, 2010, Yokohama, Japan, 264-269.
- Wang, Y., Chen, M., Zhou, F., and Ma, E. (2002) 'High tensile ductility in a nanostructured metal', *Nature (london)*, 419(6910), 912-915.
- Wang, Y., Gupta, R., Sukiman, N., Zhang, R., Davies, C., and Birbilis, N. (2013b) 'Influence of alloyed Nd content on the corrosion of an Al-5Mg alloy', *Corrosion Science*, 73, 181-187.

- Wang, Y., and Ma, E. (2003) 'Temperature and strain rate effects on the strength and ductility of nanostructured copper', *Applied Physics Letters*, 83(15), 3165-3167.
- Wang, Y., Ma, E., Valiev, R. Z., and Zhu, Y. (2004) 'Tough nanostructured metals at cryogenic temperatures. *Advanced Materials*', 16(4), 328-331.
- Wei, W., González, S., Hashimoto, T., Prasath Babu, R., Thompson, G., and Zhou, X. (2016) 'Effect of low-temperature sensitization on the susceptibility to intergranular corrosion in AA5083 aluminum alloy', *Materials and Corrosion*, 67(4), 331-339.
- Weigel, J., and Fromm, E. (1990) 'Determination of hydrogen absorption and desorption processes in aluminum melts by continuous hydrogen activity measurements', *Metallurgical Transactions B*, 21(5), 855-860.
- Wen, S., Xing, Z., Huang, H., Li, B., Wang, W., and Nie, Z. (2009) 'The effect of erbium on the microstructure and mechanical properties of Al-Mg-Mn-Zr alloy', *Materials Science and Engineering: A*, 516(1-2), 42-49.
- Wilde, B., and Williams, E. (1971) 'The use of current/voltage curves for the study of localized corrosion and passivity breakdown on stainless steels in chloride media', *Electrochimica Acta*, 16(11), 1971-1985
- Woo, K.-D., and Kim, S.-W. (2005) 'Tensile behavior of Al- 4% Mg- 0.4% Sc- 0.5% misch metal alloy at room temperature', *Metals and Materials International*, 11(2), 95-99.
- Wu, M., Tsao, L., Shu, G., and Lin, B. (2012) 'The effects of alloying elements and microstructure on the impact toughness of powder metal steels', *Materials Science and Engineering: A*, 538, 135-144.
- Wu, Z., Song, M., and He, Y. (2009) 'Effects of Er on the microstructure and mechanical properties of an as-extruded Al-Mg alloy', *Materials Science and Engineering: A*, 504(1-2), 183-187.
- Xianchen, S., Hong, Y., and ZHANG, X. (2017) 'Microstructure and mechanical properties of Al-7Si-0.7 Mg alloy formed with an addition of (Pr+Ce)', *Journal of Rare Earths*, 35(4), 412-418.
- Xiao, D., Wang, J., Ding, D., and Yang, H. (2003) 'Effect of rare earth Ce addition on the microstructure and mechanical properties of an Al-Cu-Mg-Ag alloy', *Journal of Alloys and Compounds*, 352(1-2), 84-88.

- Xiao, L., Shimizu, K., and Kusumoto, K. (2017) 'Impact Angle dependence of erosive wear for spheroidal carbide cast iron', *Materials Transactions*, 58(7), 1032-1037.
- Xie, S., Yi, R., Guo, X., Pan, X., and Xia, X. (2015) 'The effect of lanthanum on the solidification curve and microstructure of Al-Mg alloy during eutectic solidification', *Advances in Materials Research*, 4(2), 77-85.
- Xie, S. K., Yi, R. X., Gao, Z., Xia, X., Hu, C. G., and Guo, X. Y. (2010) 'Effect of rare earth Ce on casting properties of Al-4.5 Cu Alloy', *Advanced Materials Research*, 163, 1-4.
- Xing, Z. B., Nie, Z. R., Zou, J. X., Ji, X. L., and Wang, X. D. (2007) 'Effect of trace element Er on Al-Mg and Al-Mg-Mn alloys', *Materials Science Forum*, 546, 899-904.
- Xu, C., Liang, L., Lu, B., Zhang, J., and Liang, W. (2006a) 'Effect of La on microstructure and grain-refining performance of Al-Ti-C grain refiner', *Journal of Rare Earths*, 24(5), 596-601.
- Xu, C., Xiao, W., Hanada, S., Yamagata, H., and Ma, C. (2015) 'The effect of scandium addition on microstructure and mechanical properties of Al-Si-Mg alloy: A multi-refinement modifier', *Materials Characterization*, 110, 160-169.
- XU, G.-f., MOU, S.-z., YANG, J.-j., JIN, T.-n., NIE, Z.-r., and YIN, Z.-m. (2006b) 'Effect of trace rare earth element Er on Al-Zn-Mg alloy', *Transactions of Nonferrous Metals Society of China*, 16(3), 598-603.
- Yan, G., Wenlin, C., Zhen, G., and Liang, W. (2017) 'Effect of rare earth metals on mechanical and corrosion properties of Al-Zn-Mg-Cu-Zr Alloy', *Rare Metal Materials and Engineering*, 46(8), 2070-2075.
- Yasakau, K. A., Zheludkevich, M. L., Lamaka, S. V., and Ferreira, M. G. (2007) 'Role of intermetallic phases in localized corrosion of AA5083', *Electrochimica Acta*, 52(27), 7651-7659.
- Yin, Z., Pan, Q., Zhang, Y., and Jiang, F. (2000) 'Effect of minor Sc and Zr on the microstructure and mechanical properties of Al-Mg based alloys', *Materials Science and Engineering: A*, 280(1), 151-155.
- YU, J., LU, C.-C., Chan, C.-S., and Hsu, K.-F. (2011) 'Evolution of black cauliflower-like precipitates on the surface of AA5083 slab during homogenizing', *China Steel Technical Report*, 24, 48-55.

- Yuan, W., Liang, Z., Zhang, C., and Wei, L. (2012) 'Effects of La addition on the mechanical properties and thermal-resistant properties of Al-Mg-Si-Zr alloys based on AA 6201', *Materials & Design*, 34, 788-792.
- Zakharov, M., and Rogel'berg, L. (1963) 'Effect of zinc on the susceptibility of aluminium-magnesium alloys to stress corrosion', *Metal Science and Heat Treatment*, 5(12), 692-695.
- Zamin, M. (1981) 'The role of Mn in the corrosion behavior of Al-Mn alloys', *Corrosion*, 37(11), 627-632.
- Zhang, H., Feng, J., Zhu, W., Liu, C., Xu, S., Shao, P., et al. (2000) 'Chronic toxicity of rare-earth elements on human beings', *Biological Trace Element Research*, 73(1), 1-17.
- Zhang, J., Zhao, J., and Zuo, R. (2015a) 'Microstructure and mechanical properties of micro-alloying modified Al-Mg alloys.', International Conference on Power Electronics and Energy Engineering (PEEE 2015), held on April 19-20, 2015 in Hong Kong, China, 153-156
- Zhang, M.-X., Kelly, P., Easton, M., and Taylor, J. (2005) 'Crystallographic study of grain refinement in aluminum alloys using the edge-to-edge matching model', *Acta Materialia*, 53(5), 1427-1438.
- Zhang, R., Gupta, R., Davies, C., Hodge, A., Xia, K., et al. (2015b) 'The influence of grain size and grain orientation on sensitization in AA5083', *Corrosion*, 72(2), 160-168.
- Zhang, R., Steiner, M., Agnew, S., Kairy, S., Davies, C., and Birbilis, N. (2017a) 'Experiment-based modelling of grain boundary β -phase (Mg₂Al₃) evolution during sensitisation of aluminium alloy AA5083', *Scientific Reports*, 7(1), 2961.
- Zhang, R., Zhang, Y., Yan, Y., Thomas, S., Davies, C., and Birbilis, N. (2017b) 'The effect of reversion heat treatment on the degree of sensitisation for aluminium alloy AA5083', *Corrosion Science*, 126, 324-333.
- Zhang, X., Wang, Z., Zhou, Z., and Xu, J. (2016) 'Effects of cerium and lanthanum on the corrosion behavior of Al-3.0 wt. % Mg Alloy', *Journal of Materials Engineering and Performance*, 25(3), 1122-1128.
- Zhang, X., Wang, Z., Zhou, Z., Xu, J., Zhong, Z., Yuan, H., et al. (2015c) 'Effects of Rare Earth on Microstructure and Mechanical Properties of Al-3.2 Mg Alloy', *Materials Science Forum*, 817,192-197.

- Zhang, Z., Sheng, H., Wang, Z., Gludovatz, B., Zhang, Z., George, E.P., Yu, Q., Mao, S.X. and Ritchie, R.O (2017c) ‘Dislocation mechanisms and 3D twin architectures generate exceptional strength-ductility-toughness combination in CrCoNi medium-entropy alloy’, *Nature Communications*, 8(1), 1-8.
- Zhao, J.-w., Luo, B.-h., He, K.-j., Bai, Z.-h., Li, B., and Chen, W. (2016) ‘Effects of minor Zn content on microstructure and corrosion properties of Al-Mg alloy’, *Journal of Central South University*, 23(12), 3051-3059.
- Zhao, L., Pan, Y., Liao, H., and Wang, Q. (2012) ‘Degassing of aluminum alloys during re-melting’, *Materials Letters*, 66(1), 328-331.
- Zhao, X. (2006) *Exfoliation Corrosion Kinetics of High Strength Aluminum Alloys*. PhD Thesis, Ohio State University, USA.
- Zhu, H., Dahle, A. K., and Ghosh, A. K. (2009) ‘Effect of Sc and Zn additions on microstructure and hot formability of Al-Mg sheet alloys’, *Metallurgical and Materials Transactions A*, 40 (3), 598.
- Zipperian, D. C. (2011). *Metallographic handbook*. 1st edn. PACE Technologies, Tucson, Arizona, USA.143-177.
- Zolotarevsky, V. S., Belov, N. A., and Glazoff, M. V. (2007). *Casting aluminum alloys*.1st edn. Elsevier Science, Oxford, U.K, 45.

APPENDIX O

Publications:

- 1) A. Ali Al-Bakoosh, Jamaliah Idris (2018) 'Impact of rare earth elements ce and pr addition on grain refinement of AA5083 alloy', *Journal of Chemical Technology and Metallurgy*, 53(5), 916-923.
- 2) A. Ali Al-Bakoosh and Jamaliah Idris (2018) 'Effect of cerium and praseodymium additions on impact toughness of AA5083 alloy at room temperature and sub-zero-temperature ', *Contemporary Engineering Sciences*, 11 (52), 2551-2562.
- 3) Jamaliah Idris, A.AI-Bakoosh (2014) 'Application of non-destructive testing techniques for the assessment of casting of AA5083 alloy', *Journal of Advanced Research in Applied Mechanics*, 3(1), 25-34.
- 4) I. J, A. A. Al bakoosh and S.T. Olohunde (2020) 'Effect of rare earth elements (C and Pr) addition on the eroded AA5083 alloy by a solid spherical particle impingement ', *International Journal of Advanced Science and Technology*, 29 (02), 1763-1772.
- 5) S. Olohunde, Abd. M, Idris Jamaliah, A. Ali Al-Bakoosh (2019) 'Corrosion resistance of aluminium–silicon hypereutectic alloy from scrap metal', *Journal of Bio- and Tribo-Corrosion* 5(41), 1- 8.