

**The effect of Nickel, Cobalt and Tin On the evolution
Of Microstructural and Mechanical properties
Of Al-Zn-Mg-Cu Alloys (7000 series) Via Casting,
Powder Metallurgy and Friction Stir Processing
Techniques**

HAIDER T. NAEEM

UNIVERSITI MALAYSIA PERLIS

2015



UniMAP

**The effect of Nickel, Cobalt and Tin On the evolution
Of Microstructural and Mechanical properties
Of Al-Zn-Mg-Cu Alloys (7000 series) Via Casting,
Powder Metallurgy and Friction Stir Processing
Techniques**

By

**HAIDER T. NAEEM
(1140410738)**

A thesis submitted in fulfillment of the requirements for the degree of
Doctor of Philosophy

**School of Materials Engineering
UNIVERSITI MALAYSIA PERLIS**

2015

UNIVERSITI MALAYSIA PERLIS

DECLARATION OF THESIS

Author's full name : **HAIDER T. NAEEM**

Date of birth : **18/08/1984**

Title : **THE EFFECT OF NICKEL, COBALT AND TIN ON THE EVOLUTION OF MICROSTRUCTURAL AND MECHANICAL PROPERTIES OF AL-ZN-MG-CU ALLOYS (7000 SERIES) VIA CASTING, POWDER METALLURGY AND FRICTION STIR PROCESSING TECHNIQUES**

Academic Session : **2015/2016**

I hereby declare that the thesis becomes the property of Universiti Malaysia Perlis (UniMAP) and to be placed at the library of UniMAP. This thesis is classified as:

- CONFIDENTIAL** (Contains confidential information under the Official Secret Act 1972)*
- RESTRICTED** (Contains restricted information as specified by the organization where research was done)*
- OPEN ACCESS** I agree that my thesis is to be made immediately available as hard copy or on-line open access (full text)

I, the author, give permission to the UniMAP to reproduce this thesis in whole or in part for the purpose of research or academic exchange only (except during a period of __ years, if so requested above).

Certified by:

SIGNATURE

A5402747
(NEW IC NO. / PASSPORT NO.)

SIGNATURE OF SUPERVISOR

DR. KAHTAN S. MOHAMMED
NAME OF SUPERVISOR

Date: _____

Date: _____

NOTES: * If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization with period and reasons for confidentiality or restriction.

ACKNOWLEDGEMENTS

First of all, utmost praise and thanks be to Allah (SWT) who bestowed strength and stamina to complete this project on me. I would also like to express my sincere thanks to all who have contributed to the success of this study, firstly and foremost my main supervisor; Dr. Kahtan S. Mohammed whom I feel very indebted to I am very much indebted to. It is my great pleasure to express my sincere thanks for his crucial and highly motivating directions and discussions, the extraordinary cooperation and support, besides his enriching visions and perspective about broad humanity and life issues. It has been a real pleasure to work with him, for the more I worked with him, the more I admired his character and intellects. I would also like to express my sincere appreciation for my co-supervisors; Prof. Azmi Rahmat and Dr. Khairel R. Ahmad for their motivational support and fruitful discussions. My deep appreciation and special thanks go to the Universiti Malaysia Perlis (UniMAP) and to the staff of the UniMAP; especially the staff of the School of Materials Engineering for their support and eagerness to provide the best research environment needed for my study.

Additionally, my thanks go for Iraqi Ministry of Higher Education and Scientific Research/ Al-Muthanna University for the scholarship granted through them. I need to express my sincere gratitude for my parents who devoted their lives for me, same to my wife, my children, my brothers and my sisters for their daily prayers and support, giving me the motivation and strength that I most needed to achieve my goals. I am really indebted to them all and words are not sufficed to express the gratitude I owe to them all. Special thanks go to my wife for her motivation, patience, help and support during my whole academic life.

TABLE OF CONTENTS	PAGE
DECLARATION OF THESIS	i
ACKNOWLEDGEMENTS	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	xi
LIST OF FIGURES	xiii
LIST OF ABBREVIATIONS	xxiii
LIST OF SYMBOLS	xxvi
ABSTRAK	xxvii
ABSTRACT	xxviii
CHAPTER 1 INTRODUCTION	1
1.1 Background	1
1.2 Problem Statement	5
1.3 Research Objectives	8
1.4 Research Scope	10
1.4.1 The casting route	10
1.4.2 The powder metallurgical route	10
1.4.3 Mechanical alloying route	11
1.5 Significance of the study	13
1.6 Thesis Outline	14
CHAPTER 2 LITERATURE REVIEW	16
2.1 Overview of Aluminum and its Alloys	16
2.1.1 Aluminium wrought alloys	19

2.1.1.1	Features of Al-alloy (7xxx) series	20
2.1.1.2	Phase diagram of the Al-Zn-Mg-Cu system	20
2.2	Processing of the Al-Zn-Mg-Cu alloy (7xxx) series using the casting route	24
2.2.1	Introduction of casting process of aluminum alloys	25
2.2.1.1	An overview of direct chill casting of Al-Zn-Mg-Cu alloys	25
2.2.1.2	Mechanism of refinement grain during DC casting of Aluminum alloys	27
2.2.1.3	Grain refinement during casting of Al-Zn-Mg-Cu alloys	29
2.2.2	Role of the extrusion process in Al-Zn-Mg-Cu alloys	30
2.2.2.1	Basic concepts in recrystallization mechanism of extrusion of Al-Alloys	32
2.2.2.2	The effect of extrusion action on Al-Zn-Mg-Cu alloys	33
2.3	Strengthening mechanisms for Al-Zn-Mg-Cu alloys	34
2.4	Grain size strengthening of Al-Zn-Mg-Cu alloys	35
2.5	Strengthening by precipitation hardening of Al-Zn-Mg-Cu alloys	36
2.5.1	Fundamentals of the precipitation process in Al-Zn-Mg-Cu alloys	37
2.5.2	Homogenization heat treatment of Al-Z-Mg-Cu alloys	38
2.5.3	Quenching effects on properties of the Al-Zn-Mg-Cu alloys	39
2.5.4	Precipitation hardening of Al-Zn-Mg-Cu alloys	40
2.5.4.1	The basic concepts of precipitation mechanism of the Al-Zn-Mg-Cu alloys	42
2.5.4.2	The artificial aging at T6 temper for the Al-Zn-Mg-Cu alloy	45
2.5.4.3	Studies on properties of Al-Zn-Mg-Cu alloys under the aging treatment	45
2.5.4.4	Overview of the retrogression and reaging treatment of Al-Zn-Mg-Cu alloys	46

2.6	Dispersion strengthening of the Al-Zn-Mg-Cu alloys	49
2.6.1	Dispersion strengthening effects on Al-Zn-Mg-Cu alloys	50
2.7	Producing the Al-Zn-Mg-Cu alloys using powder metallurgy route	52
2.8	Fundamentals of metal matrix composites	53
2.8.1	Aluminum and Aluminum alloy matrix composites (AMCs)	54
2.8.2	Strengthening mechanisms of reinforcement particulates of AMCs	55
2.8.2.1	Load Transfer from Matrix to Particles	55
2.8.2.2	Effect of dislocation density on strengthening	56
2.8.2.3	Overall strengthening of the Al-alloys matrix	57
2.9	Processing of the Al-Zn-Mg-Cu alloys matrix composites	57
2.9.1	Powder Metallurgy route	58
2.9.1.1	The mixing or blending stage	58
2.9.1.2	The compaction is a process	58
2.9.1.3	The sintering process	59
2.9.2	Basic principles of mechanical alloying	63
2.9.2.1	Mechanisms of Mechanical Alloying	64
2.9.2.2	Solid solubility extensions of elements during mechanical alloying	66
2.9.2.3	Production of PM Al-Zn-Mg-Cu Alloys/Composites by mechanical alloying	67
2.10	Significance of Friction Stir Processing in Al-alloys	69
2.10.1	Basic principles of friction stir processing of Al-Alloys/composites	70
2.10.2	Process parameters and properties of FSP	72
2.10.3	Evolution of microstructure and strength of Al-alloy during FSP	73
2.10.4	The development of an Al-Zn-Mg-Cu system via FSP	74

2.11	Corrosion of Aluminum and its alloys	76
2.11.1	Corrosion behaviour in Aluminum and its alloys	77
2.12	An overview of solid particle erosion/corrosion behaviour for Al-alloys	78
2.12.1	Mechanism of solid particle erosion of Al-alloys	79
CHAPTER 3 RESEARCH METHODOLOGY		81
3.1	Introduction	81
3.2	Route of Casting and Alloying Techniques	84
3.2.1	Raw materials	85
3.2.2	Classification of Al-Zn-Mg-Cu alloys	85
3.2.3	Manufacturing of different Al-Zn-Mg-Cu alloys using casting technique	86
3.2.4	Homogenizing treatments	88
3.2.5	Hot extrusion process	90
3.2.6	Heat treatment	91
3.2.6.1	Aging temper at T6	91
3.2.6.2	Retrogression and re-aging (RRA)	92
3.3	Microstructural Evaluations	93
3.3.1	Optical Microscope (OM)	93
3.3.2	Scanning Electron Microscope (SEM)	94
3.3.3	Energy dispersive X-rays spectroscopy analysis (EDS)	94
3.3.4	X-ray diffraction analysis (XRD)	94
3.4	Mechanical Testings	95
3.4.1	Vickers Hardness Testing	95
3.4.2	Tensile Strength Testing	95
3.4.3	Impact Testing	95

3.5	Corrosion and Erosion behaviour	96
3.5.1	Immersion testing	96
3.5.2	Solid Particle Erosion Testing	97
3.6	The powder Metallurgical Route	101
3.6.1	Raw materials	102
3.6.2	Fabrication of Al-Zn-Mg-Cu PM alloy	102
3.6.3	Mixing method	103
3.6.4	Mechanical alloying	104
3.6.5	Compaction process	106
3.7	Sintering process	107
3.7.1	Density and porosity analysis	108
3.8	Heat treatment	108
3.9	Samples characterization	109
3.10	The Friction Stir Processing route	110
3.10.1	Raw Materials	111
3.11	Specimens' Fabrication using Friction Stir Processing (FSP)	111
3.11.1	Modification of Al-Zn-Mg-Cu-5%Ni alloy using FSP	111
3.11.2	Fabrication of Al-Zn-Mg-Cu alloy matrix composites using FSP	114
CHAPTER 4 RESULTS AND DISCUSSIONS		119
4.1	Introduction	119
4.2	Microstructural analysis	121
4.2.1	The microstructure of Al-Zn-Mg-Cu alloys with and without Ni, Sn and Co additions produced by semi D.C casting	121
4.2.2	The microstructure of Al-1, 2, 3, 4, and 5 alloys after aging at T6 and RRA	132

4.2.3	The XRD analysis of Al-alloys with and without additives after the T6 and RRA	136
4.2.4	Microstructure of Al-alloys after hot extrusion and subsequent heat treatments	141
4.3	Mechanical properties	143
4.3.1	The mechanical properties of the heat treated Al-alloy samples as compared to those extruded then heat treated samples	143
4.3.2	The impact fracture energy and the fractured surfaces for heat treated Al-alloys	149
4.3.3	The fracture surfaces of the Al-alloys after heat treatment	150
4.4	Production of Al-Zn-Mg-Cu alloys via mixing powder metallurgy route	157
4.4.1	Microstructure of the sintered Al-Zn-Mg-Cu mix with different additives	157
4.4.2	XRD patterns of alloys A, B and C under the effects of sintering, T6 and RRA	159
4.4.3	The effect of Al_2O_{3p} on the PM Al-alloy composites properties after sintering, T6 and RRA	162
4.4.4	XRD patterns for D and E Al alloy composites after sintering, T6 and RRA	166
4.4.5	The Hardness of alloys A, B, C, D and E after sintering, T6 and RRA	168
4.5	Fabrication of the ball milled Al-Zn-Mg-Cu alloys with and without additives	170
4.5.1	Effects of Mechanical alloying (MA) on microstructural of A, B, C and composites D and E alloys	170
4.5.2	XRD analyses of the BM mixture alloy A and B; and composites D and E	177
4.5.3	The Effect of sintering, T6 and RRA on the microstructure of A, B, C, and composites D and E of BM powder	183
4.5.4	XRD patterns of the BM A, B, C and composites D and E sintered compacts after T6 and RRA	189

4.5.5	The effects of sintering and subsequent T6 and RRA on hardness of the BM alloys	194
4.6	Mechanical alloying of Al-Zn-Mg-Cu mixtures of 3, 5, 7 wt. % Ni additions.	197
4.6.1	The effects of milling time on the microstructures of MA A, B and C alloy mixtures	197
4.6.2	XRD analyses for the intermetallics of A, B and C milled mixtures after 4, 8 and 12 hrs of milling time	203
4.7	Modification Al-Zn-Mg-Cu-5%wt.Ni alloy via friction stir processing	207
4.7.1	The Effects of FSP on the microstructure of casted and heat treated Al-Zn-Mg-Cu-5wt.%Ni alloys	207
4.7.2	XRD analyses for alloy I and the FSPed alloy II after heat treatment	214
4.7.3	Effects of FSP and heat treatment on hardness of the Al-Zn-Mg-Cu-5%Ni alloys	216
4.8	Fabrication of composites of Al-7075 alloy reinforced with the MA A , B , and C mixtures	218
4.8.1	Effects of MA A , B and C reinforcements on the microstructure of Al-7075 composites	218
4.8.2	Effects of T6 and RRA on the microstructure of the FSPed Al-7075 reinforced by A , B , and C MA particles composites	223
4.8.3	XRD analyses of the FSPed Al alloy–particulates reinforcement composites after T6 and RRA	225
4.8.4	Hardness of the Al7075/reinforcement composites after FSP followed by heat treatment	229
4.9	Corrosion behaviour of Al-Zn-Mg-Cu systems	231
4.9.1	Corrosion resistance of the heat treated and extruded Al-alloys	231
4.9.2	Corrosion resistance of the mixed and milled PM Al-alloys after heat treatment	237
4.10	Solid particles erosion rates of Al-Zn-Mg-Cu systems at different conditions	240

4.10.1	Erosion resistance of the heat treated and extruded Al-alloys at impact angles 45 and 90 in slurry medium	240
4.10.2	Erosion behavior of samples of as mixed and BM Al-alloys powder underwent T6 and RRA heat treatments	245
4.10.3	Erosion resistance of FSPed Al-7075/composites samples underwent T6 and RRA	249
CHAPTER 5 CONCOLUSIONS AND FUTURE WORKS		252
5.1	Conclusions	252
5.2	Future works	254
REFERENCE		255
APPENDIX A		285
APPENDIX B		297
APPENDIX C		299
LIST OF PUBLICATIONS		302

LIST OF TABLES

NO.		PAGE
2.1	The solid solubility of different elements in Aluminum (Polmear, 2005).	18
2.2	Non-variant phase reactions of Al-Mg-Zn system (Zolotorevsky et al., 2010).	21
2.3	Solubility of Zn and Mg in solid Al (Zolotorevsky et al., 2010).	22
2.4	Non-variant reactions in quaternary alloys of Al-Cu-Mg-Zn system (Zolotorevsky et al., 2010).	24
3.1	The chemical composition of the as received AA 7075 Al-alloy in wt. %.	85
3.2	The chemical composition of the types of Al-Zn-Mg-Cu alloys in this study.	86
3.3	Solid particle erosion test parameters.	98
3.4	Ratios percentage for compositions of PM Al-Zn-Mg-Cu alloys.	103
3.5	Presents the nominal composition of Al-Zn-Mg-Cu-Ni alloy.	111
3.6	Composition ratios of different Al-Zn-Mg-Cu-Ni mixtures.	114
3.7	Summarizing coding of specimens of the Al-Zn-Mg-Cu alloys/composites which underwent the different mechanical and heat treatments.	118
4.1	Hardness and tensile strength of different Al-alloys samples after heat treatment and hot extrusion conditions.	147
4.2	The values of d of Al peak at {111} plane, crystallite size, and microstrain of the alloying mixtures and composites after 5h of BM.	180
A-1	The physical properties of the powders.	285
B-1	Present corrosion rate of the heat treated and extruded Al-alloys for different immersion times in 1.0 M HCl acid solution.	297
B-2	Present corrosion rates of the mixed and milled PM Al-alloys for different immersion times in 1.0 M HCl acid solution.	298
C-1	Present solid particles erosion rate of the heat treated and extruded Al-alloys at different impact angles in the slurry with 3 wt. % Silica sand.	299
C-2	Present solid particles erosion rate of the mixed and milled PM Al-alloys at different impact angles in the slurry medium.	300
C-3	Present erosion rate of the FSPed Al7075-alloy composites reinforced intermetallic milled powders A , B and C at different impact angles.	301

LIST OF FIGURES

NO.		PAGE
1.1	Shows the global consumption of aluminium and its alloys for the time period of 2003 to 2030 (Luo & Soria, 2007).	1
1.2	Flows chart of the progress of the operations the research.	12
2.1	Classification of aluminum alloys (Handbook committee, 1995).	19
2.2	Phase diagrams of the Al-Mg-Zn: (a) the liquidus projection; (b) and (c) distribution of phase in the solid state (Zolotarevsky et al., 2010; A. Handbook, 1992).	21
2.3	Al-Cu-Mg-Zn phase diagram (a) polythermal diagram, (b) distribution of phase fields in the solid state in the aluminum corner, and (c) single-phase domains (Zolotarevsky et al., 2010).	23
2.4	Schematic diagram shows the direct chill casting process (Nadella et al., 2008).	26
2.5	The structure of Al-1.8 wt. % Cu alloy at cooling rates of 0.4 K/s (a) and 13 K/s (b) grain size D , dendrite arm d ; (c) dendrite at quenching of an Al-3% Si (D.Eskin, 2010).	28
2.6	Types of extrusion: (a) direct; (b) indirect (Bolton, 1994).	31
2.7	Coherency types within Al-alloy matrix (a) fully coherent particles, (b) coherent particles, (c) partially coherent particles, (d) non-coherent particles (Martinsen, 2011).	43
2.8	Schematic presentation of dislocation motion: (a) curling round of the stress field from precipitates or dispersoids (b) movement passing between widely separated particles (Smallman & Ngan, 2011).	50
2.9	Several kinds of metal matrix composites (Chawla & Chawla, 2006).	54
2.10	Basic steps in making parts by powder metallurgy.	59
2.11	Two sphere-sintering models (a), micrograph of the sintering neck (b) (Z. Z. Fang, 2010).	61
2.12	Ball-powder-ball collision of powder mixture during MA (Lü et al., 1995).	66

2.13	A schematic drawing of the friction stir processing (a); different regions of FSP (b) (S. R. Sharma, 2005; Yadav & Bauri, 2012).	71
2.14	Optical microstructure of Al-Si alloy (a) base metal before FSP, (b) the stir zone of FSP at a single pass (Rao et al., 2013).	74
2.15	Electrochemical reactions of aluminum in hydrochloride acid (Fontana, 2005).	76
2.16	Pourbaix diagram of Al in pure water illustrates that the oxide film is unstable in low and high pH environments. The oxide film dissolves and Al oxidation is controlled by an aluminate reaction in a strong alkali environment (Fontana, 2005).	78
2.17	(a) Influence of impact angle on erosion of Al and glass by particle spheres at 10 m/s; (b) volume-loss rate versus time curves for various types (Shiple & Becker, 2002).	80
2.18	(a) Surface of 1020 steel eroded by SiC at 30° impact angle; (b) aluminum eroded by spherical steel shots at 60° impact angle (Shiple & Becker, 2002).	80
3.1	Flow chart summarizing the methodologies followed in this study.	83
3.2	Flow chart of the conventional metallurgy route.	84
3.3	Al-Zn-Mg-Cu alloys with and without additives produced by semi DCC (a) the rectangular steel mould (b) fixtures (c) the cylindrical steel mould.	87
3.4	Scheme of homogenization treatment of Al-Zn-Mg-Cu alloys (1, 2, 3, 4, 5).	89
3.5	(a) Scheme the progress of extrusion operations for the Al-Zn-Mg-Cu alloys 1, 2, 3, 4, and 5; (b) the extrusion mould dimension.	90
3.6	Scheme of the aging temper (T6) applied for all homogenized extruded and non-extruded Al-alloys groups.	92
3.7	Scheme of the retrogression and reaging process (RRA) for all groups of the homogenized alloys and the extruded alloys (a); the progress of heat treatment.	93
3.8	The immersion test.	97
3.9	System of solid particle erosion test.	99
3.10	Flow chart of the powder metallurgy route.	101

3.11	Optical graphs show the production stages of the mechanically alloyed Al-alloys via ball milling.	105
3.12	(a) Scheme of the steel mould (b) the compaction process up to sintering.	106
3.13	The designed diagram of the sintering process.	107
3.14	The homogenization treatment for both the mixed and the MA milled Al-Zn-Mg-Cu alloy samples.	109
3.15	Flow chart of the third route of this study.	110
3.16	FSP tool configuration.	112
3.17	Optgraph of the FSP of Al-Zn-Mg-Cu-5%Ni alloy in progress.	113
3.18	The V-shape channel in Al7075 plate alloy (a); Pinless shoulder with its dimensions (b).	115
3.19	The FSP production steps of Al-7075 composite reinforced by the intermetallic milled Al-Zn-Mg-Cu-3, 5, 7 % wt. Ni.	117
4.1	Scope's summary of this chapter.	120
4.2	Optical graph of the microstructure of the as received Al7075 alloy.	121
4.3	Optical microstructures of the as quenched Al-alloy1 sample.	122
4.4	Optical microstructures of the as quenched Al-alloy2 sample.	123
4.5	Optical microstructures of the as quenched Al-alloy3 sample.	123
4.6	Optical microstructures for the as quenched Al-alloy4 sample.	124
4.7	Optical micrograph reveals the microstructure of the as quenched Al-alloy5 sample.	124
4.8	The average grain size of the as quenched Al-Zn-Mg-Cu alloys.	125
4.9	The (a) and (b) SEM micrograph and (c) EDS of the as quenched alloy1.	127
4.10	The (a) SEM micrograph and (b) the EDS analysis of the as quenched alloy2.	128
4.11	The (a) SEM micrograph and (b) EDS scan analysis of the as quenched alloy3.	129
4.12	The (a) SEM micrograph and (b) EDS spectrum of the as quenched alloy4.	130

4.13	SEM micrograph (a); EDS spectrum (b) of the as quenched alloy5 sample.	131
4.14	The (a) SEM and (b) EDS analysis of alloy1 sample after the T6 temper.	132
4.15	The (a) SEM micrograph and (b) EDS scan analysis of alloy1 sample after RRA.	133
4.16	The (a) SEM micrograph and (b) EDS of Al-alloy3 that underwent the T6.	134
4.17	The (a) SEM micrograph and (b) EDS analysis of the aged alloy4 sample.	135
4.18	The XRD plots of Al-alloy1 after (a) quenching, (b) T6, and (c) RRA process.	137
4.19	The XRD plots of Al-alloy3 samples after quenching, T6 temper and RRA.	138
4.20	The XRD plots of Al-alloy4 after (a) quenching, (b) T6, and (c) RRA.	139
4.21	The XRD plots for Al-alloy5 after quenching, the T6 temper and RRA.	140
4.22	The (a-c) SEM micrograph; (b) the EDS of the extruded alloy3 after the T6.	141
4.23	The (a) (b) and (c) SEM micrograph and the (d) and (e) EDS of the extruded alloy5 after RRA.	142
4.24	Variations of the tensile strength for Al-alloy1 after various heat treatment and extrusion operations.	144
4.25	Vickers hardness for the base Al-alloy1 specimens after different heat treatments.	145
4.26	Impact energies for different Al-alloys that underwent different heat treatments.	150
4.27	The SEM fractographs of alloy1 (a) the as quenched; (b) the aged at T6.	152
4.28	The SEM fractographs of alloy3 after (a) the as quenched; (b) the aged at T6.	153
4.29	The SEM fractographs of alloy4; (a) the as quenched; (b) the RRA.	155

4.30	The SEM fractographs of alloy5 (a) the as quenched and (b) the aged at T6.	156
4.31(a)	The OM of the microstructure of alloy (A) sintered compact.	158
4.31(b)	The OM of the microstructure of alloy (C) sintered compact.	158
4.32	The XRD plots of the alloy A after sintering, T6, and RRA.	160
4.33	The XRD plots of alloy B after sintering, T6, and RRA.	161
4.34	The XRD plots of the as mixed alloy C; as sintering, the T6, and RRA.	162
4.35	The OM of the microstructure of the sintered alloy composites D (a) and E (b).	163
4.36	(a) and (b) SEM and (c) and (d) EDS scans of the alloy composite D after the sintering.	164
4.37	(a) and (b) SEM and (c) EDS of the alloy composite E after the sintering.	165
4.38	The XRD plots of the alloy composite D after the sintering, T6 and RRA.	166
4.39	The XRD plots of the alloy composite E; after the sintering, T6 and RRA.	167
4.40	Hardness of alloy A, B, C, D and E after sintering, the T6 and RRA process.	168
4.41	(a) The SEM micrograph (b) the EDS analysis of alloy A BM mixture after 5 hrs milling time.	171
4.42	The powder morphology of the BM alloy B after milling for 5 hrs; (a) SEM micrograph and (b) EDS scan analysis.	172
4.43	The (a) SEM micrograph and (b) EDS of alloy C BM powder.	173
4.44	The SEM images in (a), (b) and (c); the EDS analysis in (d) and (e) of the BM mixture of alloy composite D.	175
4.45	(a) SEM image and (b) the EDS spot scan analysis of the BM alloy composite E mixture.	176
4.46	(a) The XRD patterns of alloy A mixture of as mixed and after BM of 5 hrs (b) shifting in Bragg's angle of first peak at plane {111}.	178
4.47	(a) The XRD patterns of the as mixed Al alloy B mixture and after 5 hrs of BM (b) shifting in the Bragg's angle of first peak at plane {111}.	179

4.48	(a) The XRD patterns of composite D powder alloy; the as mixed and the 5hrs BM powder alloy (b) the shift in Bragg's angle of first peak at plane {111} is evident.	182
4.49	(a) The SEM and (b) the EDS scan of alloy B sintered compact of BM powder.	183
4.50	Variations of the sintered densities of A, B and C alloys compacts of as mixed and BM constituents.	184
4.51	The (a) SEM and (b) the EDS area scan of composite D alloy sintered.	185
4.52	(a) and (b) SEM and (c) the EDS scan of composite E alloy sintered compact.	186
4.53	(a) The SEM of the composite D alloy sintered compact after aging at T6.	187
4.54	(a) The SEM and (b) the EDS scan analysis for sintered compacts of composite E alloy after RRA heat treatment.	188
4.55	The XRD plots of sintered compacts of BM alloy A powder (a) as sintered, (b) after the T6 and (c) after RRA.	189
4.56	The XRD patterns of sintered compacts of alloy B BM powder after T6, and RRA.	190
4.57	The XRD patterns of the BM alloy C compacts (a) the as sintered compact (b) after the T6 (c) after RRA.	191
4.58	The XRD patterns of BM alloy D compacts (a) as sintered compact (b) after the T6 aging (c) after RRA process.	192
4.59	The XRD patterns of BM alloy E compacts (a) as sintered compact (b) after the T6 aging (c) after RRA process.	193
4.60	Vickers hardness of sintered compacts of A, B, C and composites D and E BM powder after T6 and RRA treatments.	194
4.61	The SEM (a) the as-mixed powder (b) BM powders of alloy A (c) the EDS analysis of the BM particles of alloy A at milling time of 4 hrs.	198
4.62	The (a) SEM and (b) EDS of the BM mixture A at milling of 8 hrs.	199
4.63	The SEM of the BM mixture A at milling of 12h.	199
4.64	The (a) SEM and (b) EDS of BM mixture B at milling time of 8h.	200
4.65	(a) The SEM morphology and (b) the EDS microanalysis of BM mixture B at milling time of 12 hrs.	201

4.66	(a) The SEM morphology (b) the EDS microanalysis of the milled mixture C underwent BM for 4 hrs.	202
4.67	(a) The SEM morphology (b) EDS scan analysis of the milled mixture C particles at milling time of 12 hrs.	202
4.68	The XRD patterns of the milled alloy A mixture after different milling times.	204
4.69	The XRD patterns of the BM alloy B mixture after 4, 8, and 12 hrs of milling.	205
4.70	The XRD patterns of the alloy C mixture after 4, 8, and 12 hrs of milling.	206
4.71	(a) OM of the as quenched alloy I , (b) SEM of micrograph and (c) EDS.	208
4.72	The (a) OM; (b) SEM micrograph and (c) EDS analysis of alloy I showing intercompounds within microstructure after the age tempering at T6.	209
4.73	(a) OM of the FSPed alloy II shows different microstructural zones; (b) SEM micrograph (c) the EDS spectrum analysis of the SZ.	211
4.74	(a) The SEM micrograph and (b) The EDS analysis of the SZ for the FSPed alloy II after RRA.	213
4.75	The XRD plots of alloy I ; (a) as quenched (b) after the T6 (c) after RRA treatment	214
4.76	The XRD patterns for alloy II after FSP, T6, and RRA.	215
4.77	Hardness of Al-alloys I and the FSPed alloy II after T6 and RRA.	217
4.78	The (a) OM of the as received Al7075-alloy microstructure (b) and (c) superimposed collage OM images of the FSPed surface of MA A particles reinforced Al7075-alloy.	220
4.79	The (a) OM of the FSPed, (b-d) the collage microstructure in regions within the SZ within FSPed surface of BM C particles reinforced Al7075-alloy.	221
4.80	(a) The SEM micrograph and (b) EDS scan analysis of the FSPed Al7075/reinforced with BM C particles near the center of stir zone.	222
4.81	(a) SEM image and (b) EDS of the microstructure in the stir zone for the FSPed Al7075/reinforced by BM A particles after the T6 temper.	223

4.82	The (a) SEM and (b) EDS scan analysis of the FSPed Al7075/ reinforced by the BM C particulates after the T6 temper.	224
4.83	The XRD plots for BM A particulates reinforced Al7075 matrix after FSP, T6 and RRA application.	225
4.84	The XRD patterns of BM B particulates reinforced Al7075 matrix under FSP, T6, and RRA.	226
4.85	XRD plots for Al7075matrix/reinforced by C particulates after FSP, T6 temper, and RRA treatments.	228
4.86	Plots of Vickers hardness (Hv) values against the distance from the centerline of the SZ for Al7075/ A, B and C reinforcers after FSP and heat treatments.	230
4.87	Corrosion rates of heat treated Al-alloy1 vs. exposure time after immersion in 1[M] HCl.	232
4.88	(a) The SEM image (b) EDS scan analysis of the corroded surface of the RRA H.T alloy1 sample immersed in HCl acid for 72 hrs.	233
4.89	Plots of corrosion rates of the heat treated and extruded Al-alloy3 samples due to immersion in HCl acid at different exposure time	234
4.90	(a) the SEM image and (b) the EDS analysis of the corroded surface of the Al-alloy-0.5Ni underwent RRA treatment, immersed in 1[M] HCl for 72 hrs.	235
4.91	Corrosion rates of the heat treated and extruded Al-alloy5 specimens vs. exposure time in 1 [M] HCl.	236
4.92	Plots of corrosion rates of as mixed and BM Al-alloy A sintered specimens underwent heat treatment vs. exposure time in 1 [M] HCl solution.	237
4.93	Plots of corrosion rates of as mixed and BM Al-alloy B sintered specimens underwent heat treatment vs. exposure time in 1 [M] HCl solution.	238
4.94	Corrosion rates' plots of samples of as mixed and BM Al-alloy composite D underwent aging at T6 and RRA treatment.	239
4.95	Erosion rates of the heat treated and extruded Al-alloy1	241
4.96	Optical macrostructure showing the appearance of the eroded surface of the extruded Al-alloy1 sample underwent T6 at (a) 90° and (b) 45° impact angle.	242
4.97	Erosion rates of Al-alloy3 underwent different heat treatments.	243

4.98	Erosion rates of Al-alloy5 underwent different heat treatments.	244
4.99	OM of the eroded surface of the T6-H.T Al-alloy5 at (a) 90° and (b) 45°.	245
4.100	Erosion rates at impact angles of 90° and 45° for samples of as mixed and ball milled Al-alloy A underwent different heat treatments.	246
4.101	OM of the eroded surface for sintered sample of T6#BM alloy A powder at (a) 90° and (b) 45°.	246
4.102	Erosion rates of sintered samples of as mixed and ball milled Al-alloy C powder at angles of 90° and 45°.	247
4.103	Erosion rates of sintered samples of as mixed and BM alloy composites E powder underwent heat treatment at impact angles of 90° and 45°.	248
4.104	Erosion rates of FSPed sample of Al7075-alloy composites reinforced by the intermetallics BM A, B and C alloys at impact angles of 90° and 45°.	249
4.105	Erosion rates of FSPed sample of Al7075-composites reinforced by the intermetallics BM A, B and C alloys underwent the T6 and RRA for angles of 90° and 45°.	250
4.106	Optical micrograph of the eroded of FSPed sample's surface of Al/reinforced by BM B composite at impact angles (a) 90° and (b) 45°.	251
A-1	(a) SEM morphology and (b) Particles size distribution of Al powder.	286
A-2	(a) SEM morphology and (b) Particle size distribution of Zn powder.	287
A-3	(a) SEM morphology and (b) Particle size distribution of Mg powder.	288
A-4	(a) SEM morphology and (b) Particle size distribution of Cu powder.	289
A-5	(a) SEM morphology and (b) Particle size distribution of Ni powder.	290
A-6	(a) SEM morphology and (b) Particle size distribution of Co powder.	291
A-7	(a) SEM morphology and (b) Particle size distribution of Cr powder.	292
A-8	(a) SEM morphology and (b) Particle size distribution of Fe powder.	293
A-9	Particle size distribution of Al ₂ O ₃ particles powder.	294
A-10	The SEM morphology of the mixed; (a) alloy A; (b) alloy B; (c) alloy C; and Composites (d) alloy D and (e) alloy E.	296

LIST OF ABBREVIATIONS

Al ₂ O ₃ p	Alumina particulates
AlN	Aluminum Nitride
AMCs	Aluminum and its alloy matrix composites
APM	Aluminum powder metallurgy
B	Boron
BM	Ball milling
BPR	ball-to-powder weight ratio
C.R	Corrosion rate
CDRX	Continuous dynamic recrystallization
CEC	Cyclic extrusion compression
Co	Cobalt
CTE	Coefficient of thermal expansion
D.C	Direct chill casting
DDRX	Discontinuous dynamic recrystallization
DRV	Dynamic recovery
ECAP	Equal channel angular processing
EDS	Energy dispersive spectrometry
El%	Elongation
EM	Elastic modulus
Er	Erbium
F	The momentum or the force exerted by the fluid (the slurry jet)
FCC	Face center cubic
FSP	Friction stir processing

FSW	Friction stir welding
Gd	Germanium
Gd	Gadolinium
GDRX	Geometric dynamic recrystallization
GNDs	Geometrically necessary dislocations
GP zones	Guinier-Preston zones
HAZ	Heat-affected zone
HCl	Hydrochloride acid
Hv	Vickers hardness
Kt	Kiloton (metric)
MA	Mechanical alloying
M_f	The mass flow rate of the slurry jet
MMCs	Metal matrix composites
Ni	Nickel
ODS	Oxide dispersion strengthened
OM	Optical microstructure
PCA	Process control agent
PM	Powder metallurgy
Pf	Praseodymium
PRAMCs	Particle reinforced aluminum matrix composites
RE	Rare earth elements
RRA	The retrogression and reaging temper
RSD	The relative sintered densities
Sc	Scandium metal
SCC	Stress corrosion crack