



شبكة المعلومات الجامعية
التوثيق الإلكتروني والميكرو فيلم

بسم الله الرحمن الرحيم



HANAA ALY



شبكة المعلومات الجامعية
التوثيق الإلكتروني والميكروفيلم



شبكة المعلومات الجامعية التوثيق الإلكتروني والميكروفيلم



HANAA ALY



شبكة المعلومات الجامعية
التوثيق الإلكتروني والميكروفيلم

جامعة عين شمس التوثيق الإلكتروني والميكروفيلم

قسم

نقسم بالله العظيم أن المادة التي تم توثيقها وتسجيلها
علي هذه الأقراص المدمجة قد أعدت دون أية تغييرات



يجب أن

تحفظ هذه الأقراص المدمجة بعيدا عن الغبار



HANAA ALY



Cairo University

**THERMO-MECHANICAL PROCESSING OF Al-Mg-Si
ALLOYS THROUGH EQUAL CHANNEL ANGULAR
PRESSING FOLLOWED BY COLD ROLLING**

By

Abdulrhman Mohamed Mahmoud Ouf

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
MECHANICAL DESIGN AND PRODUCTION ENGINEERING

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2021

**THERMO-MECHANICAL PROCESSING OF Al-Mg-Si
ALLOYS THROUGH EQUAL CHANNEL ANGULAR
PRESSING FOLLOWED BY COLD ROLLING**

By

Abdulrhman Mohamed Mahmoud Ouf

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
MECHANICAL DESIGN AND PRODUCTION ENGINEERING

Under the Supervision of

Prof. Dr. Ehab Adel El-Danaf

Dr. Mamdouh Mohamed Salem

.....
Professor of Materials Engineering
Department of Mechanical Design and
Production
Faculty of Engineering, Cairo University

.....
Assistant Professor
Department of Mechanical Design and
Production
Faculty of Engineering, Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2021

**THERMO-MECHANICAL PROCESSING OF Al-Mg-Si
ALLOYS THROUGH EQUAL CHANNEL ANGULAR
PRESSING FOLLOWED BY COLD ROLLING**

By
Abdulrhman Mohamed Mahmoud Ouf

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
MECHANICAL DESIGN AND PRODUCTION ENGINEERING

Approved by the
Examining Committee

Prof. Dr. Ehab Adel El-Danaf,

Thesis Main Advisor

Prof. Dr. Abdelkhalek Atia Radwan,

Internal Examiner

Prof. Dr. Mostafa Hassan Shazly,

External Examiner

- Professor of Mechanical Engineering
Faculty of Engineering, The British University in Egypt

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2021

Engineer's Name: Abdulrhman Mohamed Mahmoud Ouf
Date of Birth: 14/7/1992
Nationality: Egyptian
E-mail: abdulrhman_ouf@eng.cu.edu.eg
Phone: +201271204645
Address: 26- Ismaeel Abu Gabal St. – El-Sayeda Zeinab
Registration Date: 1/10/2016
Awarding Date:/..../2021
Degree: Master of Science
Department: Mechanical Design and Production Engineering



Supervisors:

Prof. Dr. Ehab Adel El-Danaf
Dr. Mamdouh Mohamed Salem

Examiners:

Prof. Dr. Ehab Adel El-Danaf (Thesis main advisor)
Prof. Abdelkhalek Atia Radwan (Internal examiner)
Prof. Dr. Mostafa Hassan Shazly (External examiner)
- Professor of Mechanical Engineering, Faculty of Engineering, The British University in Egypt

Title of Thesis:

Thermo-Mechanical Processing Of Al-Mg-Si Alloys Through Equal Channel Angular Pressing Followed By Cold Rolling

Key Words:

SPD; Aluminum Alloys; ECAP; Cold Rolling; Precipitation Hardening

Summary:

This thesis aims to investigate the effect of thermo-mechanical processing through equal channel angular pressing (ECAP) followed by cold rolling on the mechanical properties of some Al-Mg-Si alloys. A combination of different heat treatments, ECAP levels and cold rolling reductions was performed on the alloys. First, the effect of 1 ECAP pass followed by different rolling reductions was investigated for AA6101. The effect of different ECAP processing routes for 4 passes followed by 50% rolling reduction was also investigated for AA6101. It was found that the alloy could withstand large plastic strain without cracking, with a significant improvement in the yield strength and ultimate tensile strength. A third study investigated the effect of combining two heat treatments with two ECAP levels and two rolling levels on AA6061. Under-aged samples deformed through 1 ECAP pass followed by 40% rolling reduction exhibited a significant improvement in both the YS and UTS. On the other hand, it was remarked that the strength of over-aged AA6061 samples did not significantly increase after ECAP processing. Finally, the effect of 1 and 2 ECAP passes on the aging curve of the AA6061 was investigated. It was found that ECAP has accelerated the aging of the alloy and improved the mechanical properties.

Disclaimer

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledged all sources used and have cited them in the references section.

Name: Abdulrhman Mohamed Mahmoud Ouf

Date: .././...

Signature:

Dedication

To my father and mother for their pushing and support.

To my sister, her husband and their son.

To my fiancée', who brought much joy into my life.

To all my loving family.

To my colleagues who shared the journey with me.

To my professors and my supervisors.

And to all my friends.

Thank you all for being in my life!

Acknowledgments

I would like to show my deep appreciation and respect to my supervisors, Prof. Dr. Ehab El-Danaf and Dr. Mamdouh Salem, for their valuable guidance, support, and encouragement throughout my MSc degree. I would also like to thank Prof. Dr. Ragaie Rashad for the help with the faculty workshop facilities and also Prof. Dr. Chahinaz Saleh for providing the help with elasticity and plasticity lab.

I would like to thank Prof. Dr. Ahmed Ismaeel at the Metallurgical Research and Development Center – El Tebin for his help and support regarding the cold rolling facility. I would also like to thank Dr. Hayam Abokasha Ali for her help with the chemical analysis of the specimens.

I would like also to thank the individuals at the material mechanical testing lab, and also at the faculty workshop for the help with the experimental work.

Table of Contents

DISCLAIMER	I
DEDICATION	II
ACKNOWLEDGMENTS	III
TABLE OF CONTENTS	IV
LIST OF TABLES	VI
LIST OF FIGURES	VII
NOMENCLATURE	IX
ABSTRACT	X
CHAPTER 1 : INTRODUCTION	1
1.1. SEVERE PLASTIC DEFORMATION (SPD).....	1
1.2. ECAP OF ALUMINUM ALLOYS.....	2
1.3. WORK MOTIVATION.....	2
1.4. ORGANIZATION OF THE THESIS	3
CHAPTER 2 : LITERATURE REVIEW	4
2.1. INTRODUCTION.....	4
2.1.1. High Pressure Torsion (HPT):	5
2.1.2. Accumulative Roll Bonding (ARB):.....	6
2.1.3. Equal Channel Angular Pressing (ECAP):	6
2.1.4. Other SPD Techniques:.....	7
2.2. EQUAL CHANNEL ANGULAR PRESSING (ECAP)	8
2.2.1. Experimental Factors Affecting ECAP.....	9
2.2.1.1. Effect of the Channel Angle (ϕ):.....	9
2.2.1.2. Effect of the Angle of Curvature (ψ):.....	10
2.2.1.3. Effect of Pressing Speed:	11
2.2.1.4. Effect of Pressing Temperature:.....	11
2.2.2. Fundamental Parameters of ECAP.....	11
2.2.2.1. Strain Imposed per Pass in ECAP:	11
2.2.2.2. ECAP Processing Routes:	13
2.2.3. Different Dies for ECAP.....	13
2.2.3.1. ECAP Using a Rotary Die:	14
2.2.3.2. Side Extrusion ECAP Die:	14
2.2.3.3. Multi-Pass ECAP Die:	15
2.2.4. Mechanism of Grain Refinement in ECAP.....	15
2.2.5. The Effect of ECAP Processing on the Microstructure	16
2.2.6. The Effect of ECAP on the Mechanical Properties.....	17
2.2.7. Superplastic Behavior	19
2.3. ECAP PROCESSING ON VARIOUS ALUMINUM ALLOYS	21
2.4. ECAP PROCESSING FOLLOWED BY ANOTHER FORMING OPERATION	23
2.5. ECAP PROCESSING COMBINED WITH HEAT TREATMENT	26

2.6.	THESIS OBJECTIVE	28
CHAPTER 3 : MATERIALS AND EQUIPMENT		29
3.1.	ALUMINUM ALLOY 6061	30
3.2.	ALUMINUM ALLOY 6101	33
3.3.	ECAP DIE.....	34
3.3.1.	Die Design	35
3.3.2.	Finite Element Analysis of the Die	36
3.3.3.	Die Manufacturing.....	40
3.4.	THE ROLLING MACHINE.....	42
3.5.	OTHER USED EQUIPMENT	43
3.5.1.	Universal Testing Machine for ECAP	43
3.5.2.	Vickers Hardness Tester	43
3.5.3.	Electric Furnace for Heat Treatment.....	44
3.5.4.	Universal Testing Machine for Tensile Testing.....	44
CHAPTER 4 : EXPERIMENTAL PROCEDURE		45
4.1.	INTRODUCTION.....	45
4.2.	AA 6101	45
4.2.1.	Study 1: Cold Rolling Effect after 1 ECAP Pass on AA 6101	45
4.2.2.	Study 2: Effect of ECAP Routes & Rolling on AA 6101	46
4.3.	AA 6061	47
4.3.1.	Study 3: Effect of UA & OA before ECAP & Rolling on AA 6061	47
4.3.2.	Study 4: Effect of ECAP on Aging Behavior of AA 6061	48
4.4.	ADDITIONAL SAMPLES	49
4.5.	MECHANICAL TESTING PROCEDURE	50
4.5.1.	Tensile Samples Preparation.....	50
4.5.2.	Tensile Testing.....	52
4.6.	FRACTOGRAPHY TESTS	52
CHAPTER 5 : RESULTS AND DISCUSSIONS		53
5.1.	AA 6101	53
5.1.1.	Cold Rolling Effect after 1 ECAP Pass on AA 6101	53
5.1.2.	The Effect of ECAP Routes & Rolling on AA 6101	57
5.2.	AA 6061	62
5.2.1.	The Effect of UA & OA before ECAP & Rolling on AA 6061.....	62
5.2.2.	The Effect of ECAP on Aging Behaviour of AA 6061.....	70
CHAPTER 6 : CONCLUSIONS AND FUTURE WORK		73
REFERENCES		75
APPENDIX A: ECAP DIE DRAWINGS.....		78

List of Tables

Table 3. 1: Standard chemical composition for AA 6061 [32]	30
Table 3. 2: Actual chemical composition for the used AA 6061	31
Table 3. 3: Hardness results for different under-aging conditions	33
Table 3. 4: Hardness results for different over-aging conditions	33
Table 3. 5: Standard chemical composition for AA 6101 [33]	34
Table 3. 6: Actual chemical composition for the used AA 6101	34
Table 4. 1: Rolling reduction % & total strain for the 7 samples after 1 ECAP pass .	46
Table 4. 2: Design of experiment for study 3 on AA 6061	48
Table 5. 1: The mechanical properties of the 7 rolled specimens and the initial condition specimens	54
Table 5. 2: YS and UTS for specimens ECAPed for 4 passes without and with 50 % reduction and ECAPed for 1 pass with 50% and 77.3% reduction	58
Table 5. 3: YS, UTS, EL% and Total strain for the UA specimens with different ECAP and rolling % and for the as received T6 condition.....	63
Table 5. 4: YS, UTS and EL% for the OA condition after ECAP for 1 and 2 passes with the UA and T6 conditions.....	64
Table 5. 5: YS, UTS and EL% for OA specimens after 1 and 2 ECAP passes and rolling	66
Table 5. 6: YS, UTS and EL% for AA 6061 in the SST, T6, T8 for 1 pass and T8 for 2 passes conditions	72

List of Figures

Fig. 2. 1: Disc sample processing by high pressure torsion (HPT) [2]	5
Fig. 2. 2: (a) The principle of accumulative roll bonding (ARB) [4] (b) The principle of equal channel angular pressing (ECAP) [7]	6
Fig. 2. 3: (a) The repetitive corrugating and straightening process (RCS) [4] (b) The principle of multi-directional forging technique (MDF) [6]	7
Fig. 2. 4: The ECAP principle showing the coordinate system and the pressed sample [2]	8
Fig. 2. 5: A 2-D illustration of ECAP dies with different channel angle (ϕ) values; (a) $\phi = 90^\circ$, (b) $\phi = 112.5^\circ$, (c) $\phi = 135^\circ$, (d) $\phi = 157.5^\circ$ [10] and (e) $\phi = 60^\circ$ [8].....	9
Fig. 2. 6: A 2-D illustration of ECAP dies with certain (ϕ) and different values of curvature angle (ψ); (a) $\psi = 0^\circ$, (b) $\psi = (\pi - \phi)^\circ$ and (c) ψ has an arbitrary value such that: $0^\circ < \psi < (\pi - \phi)^\circ$ [9]	10
Fig. 2. 7: The effect of (ϕ) and (ψ) on the equivalent strain in ECAP using one pass ($N = 1$); ϕ varies between 45° and 180° and ψ varies from 0° to 90° [8].....	12
Fig. 2. 8: The main four routes for ECAP processing [7]	13
Fig. 2. 9: Rotary die for ECAP processing; (a) initial case, (b) after first pass and (c) after die rotation by 90° clockwise and ready for next pass [11]	14
Fig. 2. 10: (a) A 2-D illustration for side extrusion ECAP processing [13] (b) A 2-D illustration for multi-pass die for ECAP [12].....	15
Fig. 2. 11: OIM images for 99.99% aluminum (a) initial un-pressed state and after ECAP by (b) 1 pass, (c) 2, (d) 3, (e) 4, (f) 8 and (g) 12 passes; grain colors corresponds to unit triangle [14].....	17
Fig. 2. 12: Variation of equivalent strain with (a) 0.2% proof stress and (b) UTS [15].18	18
Fig. 2. 13: (a) The variation of the equivalent strain with elongation to fracture % for 6 aluminum alloys and (b) Comparison of proof stress and ductility for AA 3004 processed by ECAP and by cold rolling plotted against equivalent strain [15]	19
Fig. 2. 14: The occurrence of high strain rate superplasticity after ECAP processing in a commercial Al-Mg-Li-Zr alloy; the upper specimen is untested [16]	20
Fig. 2. 15: (a) Vickers hardness values for 4 AAs in the initial condition, ECAP processed by 120° die and ECAP processed by 90° die and (b) A fractured AA 7010 sample ECAP processed by 90° die after simple compression showing fractures at 45° [20]	22
Fig. 2. 16: HV vs distance from disk center for annealed condition, ECAPed for 4 passes and ECAPed for 4 passes followed by HPT for different number of turns [24].25	25
Fig. 3. 1: A typical age hardening heat treatment cycle, adapted from Callister	30
Fig. 3. 2: The variation of strength or hardness with aging time at a certain aging temperature, adapted from Callister [28].....	30
Fig. 3. 3: Representation of the heat treatment procedure carried out on AA 6061 [29]	32
Fig. 3. 4: The variation of Vickers hardness with aging time at different aging temperatures [29].....	32
Fig. 3. 5: (a) Die Assembly for the initial trial with 6 bolts, (b) Von Mises stress values for the six bolts and (c) Displacement magnitude distribution of the die	37
Fig. 3. 6: Modified wide die assembly with 6 M24 bolts and 2 M20 bolts.....	38
Fig. 3. 7: Von Mises stress values for the eight bolts in the modified wide die.....	39
Fig. 3. 8: Displacement magnitude distribution of the modified wide die	39

Fig. 3. 9: The ECAP die halves after the heat treatment	40
Fig. 3. 10: (a) The front half of the die after finishing and (b) The back half of the die after finishing.....	41
Fig. 3. 11: The rolling machine facility	42
Fig. 4. 1: Processing sequence for study 1 on AA 6101	45
Fig. 4. 2: Processing sequence for study 2 on AA 6101.....	46
Fig. 4. 3: Processing sequence for study 3 on AA 6061.....	47
Fig. 4. 4: Processing sequence for study 3 on AA 6061.....	48
Fig. 4. 5: Specimens at different stages of processing: (a) before ECAP, (b) after ECAP, (c) after rolling (20% reduction) and (d) after rolling (40% reduction).....	50
Fig. 4. 6: Circular tensile sample of 5 mm gage diameter.....	51
Fig. 4. 7: Flat tensile samples after wire cut of 6 mm gage width.....	51
Fig. 5. 1: Stress strain curves for AA 6101 in the annealed condition and after ECAP for 1 pass	53
Fig. 5. 2: Stress strain curves for AA 6101 after annealing + 1 ECAP pass and cold rolled for 7 reduction %	54
Fig. 5. 3: Fractographic examination of (a) Annealed and (b) Annealed and 1 ECAP pass	55
Fig. 5. 4: Fractographic examination of specimens after 1 ECAP pass and (a) 50% rolling reduction and (b) 77% rolling reduction	56
Fig. 5. 5: Stress strain curves for AA 6101 after ECAP for 4 passes without and with 50 % rolling for routes (a) A, (b) B _C and (c) C	57
Fig. 5. 6: YS and UTS for specimens processed by ECAP for 4 passes using different routes without and with 50% reduction	58
Fig. 5. 7: Stress strain curves for specimens after 4 ECAP passes using routes A, B _C and C + 50% reduction	59
Fig. 5. 8: Specimen ECAPed for 4 passes using route A and rolled to 50% reduction after tensile test	60
Fig. 5. 9: Fractographic examination of specimens ECAPed for 4 passes using route B _C (a) without rolling and (b) after 50% rolling reduction	61
Fig. 5. 10: Fractured UA specimens after ECAP for 2 passes and more than 12% reduction	62
Fig. 5. 11: Stress strain curves for AA 6061 specimens in the UA condition with different ECAP processing and rolling	63
Fig. 5. 12: Stress strain curves for AA 6061 for the OA specimens with 1 and 2 ECAP passes and the as received condition (T6)	64
Fig. 5. 13: Stress strain curves for AA 6061 specimens in the OA condition after ECAP for 1 and 2 passes then rolled	65
Fig. 5. 14: Fractographic examination of the UA only specimen of AA 6061	66
Fig. 5. 15: Fractographic examination of UA specimens after (a) 1 ECAP pass only and (b) 1 ECAP pass followed by 40% rolling reduction	67
Fig. 5. 16: Fractographic examination of (a) OA specimen and (b) OA specimen after 2 ECAP passes and 40% rolling reduction	69
Fig. 5. 17: Aging curves for AA 6061 at 175 °C, with no ECAP and with ECAP for 1 and 2 passes	70
Fig. 5. 18: Stress strain curves for AA 6061 in the SST, T6, T8 for 1 pass and T8 for 2 passes conditions	71
Fig. 5. 19: Fractographic examination of the T8 condition specimen after solution treatment then ECAP for 2 passes followed by peak aging	72