

**Optimisation of the heat treatment cycles of CSIR semi-solid
metal processed Al-7Si-Mg alloys A356/7**

by

Heinrich Möller

Submitted for the

Degree of Philosophiae Doctor (Metallurgical Engineering)

in the

Faculty of Engineering, Built Environment and Information Technology

UNIVERSITY OF PRETORIA

Pretoria, South Africa

2011

Submission date: 25 March 2011

SUMMARY

Title: Optimisation of the heat treatment cycles of CSIR semi-solid metal processed Al-7Si-Mg alloys A356/7

Candidate: Heinrich Möller

Supervisor: Professor Waldo E. Stumpf

Department: Materials Science and Metallurgical Engineering, University of Pretoria

Degree: Philosophiae Doctor (Metallurgical Engineering)

Conventional casting alloys Al-7Si-Mg A356/7 contain between 6.5 and 7.5% Si, together with 0.25-0.7% Mg and are used for critical castings in the automotive and aerospace industries. These alloys are also the most popular alloys used for semi-solid metal (SSM) forming due to good castability and fluidity imparted by the large volumes of the Al-Si eutectic. Despite their industrial importance, there is a lack of detailed research work revealing precipitate micro- and nanostructural evolution during aging of these alloys compared with the Al-Mg-Si 6000 series wrought alloys. This study characterises the heat treatment response of SSM-processed Al-7Si-Mg alloys in comparison with conventionally liquid cast alloys (investment casting and gravity die casting). It is shown that, provided that the maximum quantity of the alloy's Mg is placed into solid solution during solution treatment, and that the alloy's Fe content is within specification, the response to age hardening of Al-7Si-Mg alloys is independent of the processing technique used. The nanostructural evolution of Al-7Si-Mg alloys after artificial aging with and without natural pre-aging has been characterized using transmission electron microscopy and atom probe tomography and correlated with hardness and mechanical tensile properties. The number densities and Mg:Si ratios of solute clusters, GP zones and β'' -needles were determined. The heat treatment response of SSM-processed casting alloys A356/7 alloys are also compared with SSM-processed Al-Mg-Si 6000 series wrought alloys, with the advantage of having similar globular microstructures. The high Si-content of the casting alloys compared to the wrought alloys offers several advantages, including a faster artificial aging response (shorter T6 aging cycles), higher strength for comparable Mg contents and less sensitivity to prior natural aging on peak strength. Finally, an age-hardening model was developed for the Al-7Si-Mg alloys, including a method of incorporating the effects of changes in Mg-content on the aging curves.

Keywords: Al-Si-Mg alloys, heat treatment, natural aging, artificial aging, temper, semi-solid metal, rheocasting, high pressure die casting, transmission electron microscopy, atom probe tomography.

9. ACKNOWLEDGEMENTS

The following contributions are gratefully acknowledged:

- Professor Waldo Stumpf, my supervisor at the University of Pretoria, South Africa.
- Dr Sagren Govender, Research Group Leader of the Advanced Casting Technologies group at the CSIR.
- Dr Willie du Preez, Competency Area Manager of Metals and Metals Processes and Dr Liesbeth Botha, Director of Materials Science and Manufacturing at the CSIR.
- My colleagues at the CSIR who have contributed to the successful completion of this particular work: Ulyate Curle, Pierre Rossouw, Prudence Masuku, Danie Wilkins, Marius Grobler, Andre Grobler, Chris McDuling, Erich Guldenpfennig, Dr Lillian Ivanchev, Martin Williams, Peter Malesa, Sam Papo, Mary Mojalefa and Duncan Hope.
- Adrian Paine from SimLogic for assistance with ProCAST.
- Professor Rob Knutsen from the University of Cape Town, South Africa (impact testing) and Professor Chris Pistorius from Carnegie-Mellon University in Pittsburgh, United States of America (Thermo-Calc).
- The Department of Science and Technology (DST) in South Africa is acknowledged for co-funding under the Advanced Metals Initiative (AMI) Program.
- Funding from the CSIR Strategic Research Panel (SRP) “Young Researcher Establishment Fund” (YREF) is gratefully acknowledged.
- The technical, scientific and financial assistance from the AMMRF (Australian Microscopy and Microanalysis Research Facility) and specifically Dr Gang Sha, Dr Junhai Xia and Prof Simon Ringer from the University of Sydney, Australia.
- My family, the Möllers and the Roose for their continuing support.
- My wonderful wife Lida and our two gorgeous daughters Christia and Celicia for their love and support.

- Soli Deo Gloria -

TABLE OF CONTENTS

1. INTRODUCTION	1
1.1. Historical perspective	1
1.2. Heat treatment and age hardening of Al-alloys	1
1.2.1. Al-Si-Mg alloys	1
1.3. Heat treatment of Al-7Si-Mg alloys	2
1.3.1. Conventional liquid cast Al-7Si-Mg alloys	2
1.3.2. SSM-processed Al-7Si-Mg alloys	2
1.4. Objective	3
1.5. Publications	4
2. LITERATURE SURVEY	5
2.1. Semi-solid metal processing	5
2.1.1. History and introduction	5
2.1.2. Thixoforming	7
2.1.3. Rheocasting	7
2.1.3.1. CSIR rheocasting system (CSIR-RCS)	8
2.1.4. Advantages and disadvantages of SSM-processing	9
2.2. Al-7Si-Mg alloys	10
2.2.1. Influence of important alloying elements in modified Al-7Si-Mg alloys	12
2.2.1.1. Silicon	12
2.2.1.2. Magnesium	13
2.2.1.3. Iron	17
2.2.1.4. Beryllium	18
2.2.1.5. Copper	19
2.2.1.6. Manganese	20
2.2.1.7. Titanium	21
2.2.1.8. Strontium, Sodium and Antimony	22
2.3. Heat Treatment	24
2.3.1. Solution heat treatment	27
2.3.2. Quenching	33

2.3.3. Aging	36
2.3.3.1. Natural aging	38
2.3.3.2. Artificial aging	39
2.3.3.3. Influence of natural pre-aging on subsequent artificial aging	43
2.3.3.4. Heat treatment response of SSM-processed Al-7Si-Mg alloys in comparison with conventional liquid cast alloys	47
3. EXPERIMENTAL METHODS	53
3.1. Semi-solid metal processing	53
3.1.1. SSM-HPDC of rectangular plates	53
3.1.2. SSM-HPDC of automotive brake callipers	60
3.2. Investment casting of rectangular plates	62
3.3. SSM-HPDC of Al-Mg-Si wrought alloys 6082 and 6004	65
3.4. Thermo-Calc	66
3.5. Heat treatment of castings	66
3.5.1. Solution treatment	66
3.5.2. Quench after solution treatment	67
3.5.3. Natural aging and the T4 temper	67
3.5.4. Artificial aging and the T5 and T6 tempers	67
3.6. Tensile testing	68
3.6.1. The Quality Index (QI)	70
3.7. Impact testing	70
3.8. Optical microscopy and scanning electron microscopy	70
3.9. Transmission electron microscopy (TEM) and Atom probe tomography (APT)	71
4. RESULTS	73
4.1. Semi-solid metal processing	73
4.1.1. ProCAST simulation of SSM-HPDC of plates	73
4.1.2. Optical microscopy of SSM-HPDC of plates	77
4.2. Solution heat treatment	79
4.2.1. Spheroidisation of eutectic Si	79
4.2.2. Dissolution of solutes and reduction of microsegregation	85

4.2.3. Impact strength	87
4.3. Quench after solution treatment	91
4.4. Natural aging and the T4 temper	93
4.5. Artificial aging and the T6 temper	95
4.6. The effects of Mg and Fe in Al-7Si-Mg alloys	103
4.7. Artificial aging and the T5 temper	122
4.8. Comparison between different temper conditions	125
4.9. Surface liquid segregation in SSM-HPDC castings	133
4.10. SSM-HPDC of automotive brake callipers	138
4.11. Comparison of aging response of globular and dendritic Al-7Si-Mg alloys	139
4.11.1. SSM-HPDC and GDC automotive brake callipers	139
4.11.2. Investment cast plates	143
4.12. Correlations between hardness, yield strength and UTS in Al-7Si-Mg alloys	146
4.13. Comparison of aging response of SSM-HPDC Al-7Si-Mg alloys with SSM-HPDC 6000 series Al-Mg-Si wrought alloys	150
4.14. Nanostructural evolution during aging of Al-7Si-Mg alloys	156
4.14.1. Age hardening response and tensile properties	157
4.14.2. Nanostructural evaluation	159
4.14.2.1. Transmission electron microscopy (TEM)	159
4.14.2.2. Atom Probe Tomography (APT)	161
4.14.2.3. Chemical composition evolution of the matrix	164
4.14.2.4. Number density of precipitates	165
4.14.2.5. The Mg:Si ratio of clusters and precipitates in alloy F357	167
4.14.2.6. Incorporation of Al into clusters and precipitates of alloy F357	168
4.14.2.7. Incorporation of Cu into clusters and precipitates of alloy F357	168
5. DISCUSSION	171
5.1. SSM-HPDC	171
5.1.1. Rheoprocessing	171

5.1.2. High pressure die casting	171
5.2. Solution heat treatment	172
5.2.1. Spheroidisation of eutectic Si	172
5.2.2. Dissolution of solutes and reduction of microsegregation	173
5.2.3. Impact strength	174
5.3. Quench after solution treatment	175
5.4. The T6 temper condition	177
5.5. The T5 temper condition	180
5.6. Comparison of aging response of globular and dendritic Al-7Si-Mg alloys	182
5.7. Comparison of aging response of SSM-HPDC Al-7Si-Mg alloys with SSM-HPDC 6000 series Al-Mg-Si wrought alloys	183
5.8. Nanostructural evolution during aging of Al-7Si-Mg alloys	185
5.8.1. Artificial aging with natural pre-aging	185
5.8.2. Artificial aging without natural pre-aging	186
5.8.3. Comparison of artificial aging with and without natural pre-aging	186
5.9. Characteristics of precipitates in Al-7Si-Mg alloys	188
5.9.1. Solute clusters	188
5.9.2. GP zones	188
5.9.3. β'' -needles	189
5.10. Precipitation sequence of Al-7Si-Mg alloys	189
6. AGE HARDENING MODEL FOR Al-7Si-Mg ALLOYS	191
6.1. Age hardening models	191
6.2. The Shercliff-Ashby model	191
6.2.1. Calibration of the model	196
6.2.2. Application of the model in the literature	198
6.3. Application of the model in this study	200
6.4. Comparison of Al-7Si-Mg casting alloy A356 and wrought alloy 6082	205
6.5. Modelling of artificial aging curves of SSM-HPDC Al-7Si-Mg alloys with varying Mg-contents	206

7. CONCLUSIONS	210
7.1. SSM-HPDC	210
7.2. Solution heat treatment	210
7.3. Quench after solution treatment	210
7.4. Natural aging and the T4 temper condition	211
7.5. Artificial aging and the T5 temper condition	211
7.6. Artificial aging and the T6 temper condition	211
7.6.1. Artificial aging without natural pre-aging	211
7.6.2. Artificial aging with natural pre-aging	212
7.6.3. Characteristics of precipitates found in Al-7Si-Mg alloys	212
7.7. Influence of chemical composition fluctuations	212
7.8. Comparison of the aging response of globular and dendritic Al-7Si-Mg alloys	213
7.9. Comparison of the aging response of Al-7Si-Mg alloys with 6000 series wrought alloys	213
7.10. Age hardening model for Al-7Si-Mg alloys	214
8. RECOMMENDATIONS	215
8.1. SSM-HPDC	215
8.2. Solution heat treatment	215
8.3. Quench after solution treatment	215
8.4. Artificial aging and the T5 temper condition	215
8.5. Artificial aging and the T6 temper condition	216
8.6. Influence of chemical composition fluctuations	216
8.7. Age hardening model for Al-7Si-Mg alloys	216
9. ACKNOWLEDGEMENTS	217
10. REFERENCES	218