The influence of elevated Fe, Ni and Cr levels on the tensile properties of SSM-HPDC Al-Si-Mg alloy F357

MöLLER H [1*], STUMPF W E[2], PISTORIUS P C[3]

[1]Materials Science and Manufacturing, CSIR, Pretoria, South Africa
[2]Department of Materials Science and Metallurgical Engineering, University of Pretoria, South Africa
[3]Department of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh, United States of America
*Corresponding author: Tel: +27 12 841 2139, e-mail: hmoller@csir.co.za

Abstract: Al-Si-Mg alloy F357 is a popular heat treatable alloy used for semi-solid metal forming. The iron, nickel and chromium levels in these alloys are controlled to prevent the formation of intermetallic phases that have a negative influence on strength and ductility. These intermetallic phases include β-Al_5FeSi, π-$Al_8FeMg_3Si_6$, Al_9FeNi and $Al_{13}Cr_4Si_4$. In this study, microstructures and tensile properties of SSM-HPDC F357 with low and high levels of Fe, Ni and Cr are compared in different temper conditions. ThermoCalc software is used to predict the different intermetallics that can be expected in the alloys, and scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) is used to investigate the actual intermetallics that formed. The influence of these intermetallics on tensile properties is quantified. It is shown that lower strength is obtained in the alloy with high Fe, Ni and Cr levels. This is attributed mainly to the formation of more of the π-$Al_8FeMg_3Si_6$ phase, which removes strengthening Mg atoms from solid solution. Also, the ductility of the high Fe, Ni and Cr alloy is decreased significantly due to microcracking of the higher volume fraction π-$Al_8FeMg_3Si_6$ and Al_9FeNi phases. The combination of lower strength and ductility result in a decrease of the quality index of this alloy compared to the alloy with low levels of Fe, Ni and Cr.

Keywords: Semi-Solid Metal (SSM) forming, alloy F357, heat treatment, intermetallics, π-$Al_8FeMg_3Si_6$, Al_9FeNi, β-Al_5FeSi

1 Introduction

The conventional casting alloy F357 (the Be-free version of A357) is probably one of the most popular alloys used for semi-solid metal forming. This is due to its high fluidity and good “castability” [1]. The chemical composition limits of this alloy are shown in Table 1 [2].
The small additions of magnesium induce age hardening and the yield strength in the T6 condition is significantly higher than that of the binary alloy containing the same amount of silicon. Table 1 shows that iron levels are limited to a maximum of 0.20 wt% in this alloy. Iron has a low solubility in the α-Al solid solution. This causes the formation of complex intermetallic phases, the most common being β-Al_5FeSi and π-$Al_8Mg_3FeSi_6$ [3]. The negative influence of Fe on the tensile properties (of especially F357) has recently been studied by the authors [3]. The influence of Ni and Cr (and their resultant intermetallic phases) on the tensile properties of semi-solid metal high pressure die cast (SSM-HPDC) alloy F357 are not that well known. Based on the chemical composition limits shown in Table 1, both these elements are allowed to a maximum of 0.05 wt%.

In this paper, the effects of high levels of Fe, Ni and Cr on the tensile properties of SSM-HPDC plates of alloy F357 are quantified.

2 Experimental

Semi-solid metal slurries of alloy F357 (chemical composition given in Table 1) were prepared using the CSIR rheocasting process [4]. Plates (4 mm×80mm×100mm) were cast in steel moulds with a 130 ton high pressure die casting machine. The levels of Fe, Ni and Cr of batch 1 are well within the limits of the specification (Table 1). The high levels of Fe, Ni and Cr in plates of batch 2 (Table 1) were inadvertently achieved when the austenitic stainless steel sleeve tip of the Argon degasser dissolved in the F357 melt prior to casting. From Table 1 it can be seen that the Fe-content of batch 2 is above the upper limit of the specification. Although the Ni- and Cr-contents of batch 2 are still within the upper limit of the specification (<0.05 wt%), their quantities are an order of magnitude greater than for batch 1.

Table 1 Chemical composition limits for alloy F357 [2], as well as the compositions of the alloys used in this study

	Si	Mg	Fe	Cu	Mn	Zn	Ti	Other (Each)	Other (Total)
Min	6.5	0.4	-	-	-	-	0.1	-	-
Max	7.5	0.7	0.2	0.2	0.1	0.1	0.2	0.05	0.15
This study									
Batch 1	7.0	0.62	0.10	0.01	0.01	0.01	0.13	Ni = 0.004 Cr = 0.003 Sr = 0.024	
Batch 2	7.2	0.67	0.25	0.01	0.01	0.01	0.16	Ni = 0.037 Cr = 0.048 Sr = 0.037	

Thermo-Calc [5] (a commercially available software package used to perform thermodynamic and phase diagram calculations for multi-component systems of practical importance) was used to investigate the possible effects of these high Fe, Ni and Cr levels on the equilibrium phases in the alloy, using the Al-DATA ver.2 database. The tensile properties of the samples were determined using an INSTRON 1342/H1314 with 25 kN load cell capacity and an INSTRON Model 2620-602 extensometer with gauge length of 12.5mm. To determine the 0.2% proof stress, a stress rate of 10MPa/s was used and for the ultimate tensile stress (UTS) determination a displacement rate of 10mm/min. These parameters were selected based on the American Society for Testing and Materials (ASTM) standard E8M-04. Tensile specimens (dimensions can be seen in Fig. 1) were machined from the plates. A total of 5 tensile tests was used for each condition. Scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) was used to investigate the actual intermetallics that had formed in the samples. The T4 (solution treatment at 540°C for 1 h, natural aging for 5 days) and T6 (solution treatment at 540°C for 1 h, 20 h natural aging, artificial aging at 180°C for 4 h) heat treatment cycles that were used in this study were based on cycles determined by the authors in previous work [3,6].

3 Results and discussion

The calculated phase equilibria (minor phases) for the two Al-alloys of alloy F357 used in this study (Table 1) are shown in Fig. 2. In this figure, the liquidus and solidus temperatures are indicated by arrows; "pi" refers to the π phase, "beta" is β–Al_5FeSi, and "alpha" is an Al-Mn-Fe-Si solid solution based on Al_8Fe_2Si. In all cases the major phases were liquid, Al-based FCC solid solution (the primary phase upon solidification), and Si (formed by eutectic solidification).

Comparing the two diagrams in Fig. 2, it is seen that the predicted Mg_2Si content is slightly lower for batch 1 than batch 2 (this is to be expected, as the Mg-content of batch 1 is lower than that of batch 2 (Table 1). Based solely on the Mg-contents of the two alloys, the expectation is that the strength in the T6 temper of alloys from batch 2 should be slightly higher than those of batch 1 [3] (see the discussion on tensile properties later to see why this is not the case here – due to the effects of especially Fe). The higher Fe, Ni and Cr contents of batch 2 lead to significantly higher predicted quantities of phases such as π-$Al_8FeMg_3Si_6$, β-Al_5FeSi, Al_9FeNi and $Al_{13}Cr_4Si_4$ than for batch 1.

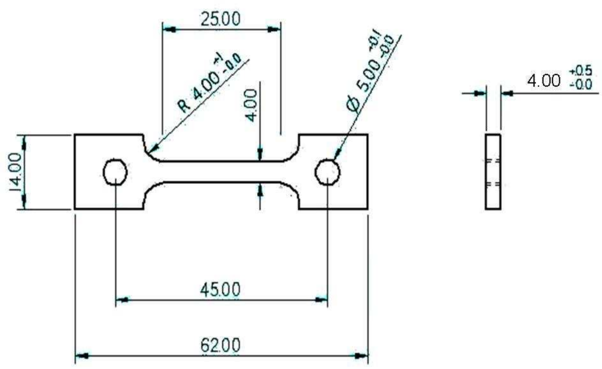

Fig.1 Dimensions (in mm) of tensile samples used in this study

Scanning electron microscopy (coupled with EDS to tentatively identify phases) was used to study the intermetallic phases in the T4 and T6 temper conditions (the intermetallics are similar in both temper conditions). Backscattered electron images of samples from both batches are shown in Fig. 3. For batch 1 (Fig. 3(a)), only β-Al_5FeSi and π-$Al_8FeMg_3Si_6$ could be identified in the eutectic (see typical EDS spectra in Fig. 4 for all qualitatively identified phases in the samples). However, for batch 2, apart from higher quantities of β-Al_5FeSi and π-$Al_8FeMg_3Si_6$, particles of Al_9FeNi could also be identified (Fig. 3(b) and Fig. 4(c)). Note that Si was also detected in the EDS of the Al_9FeNi particles. The maximum solubility of Si in this phase has been reported to be 4% [7,8].

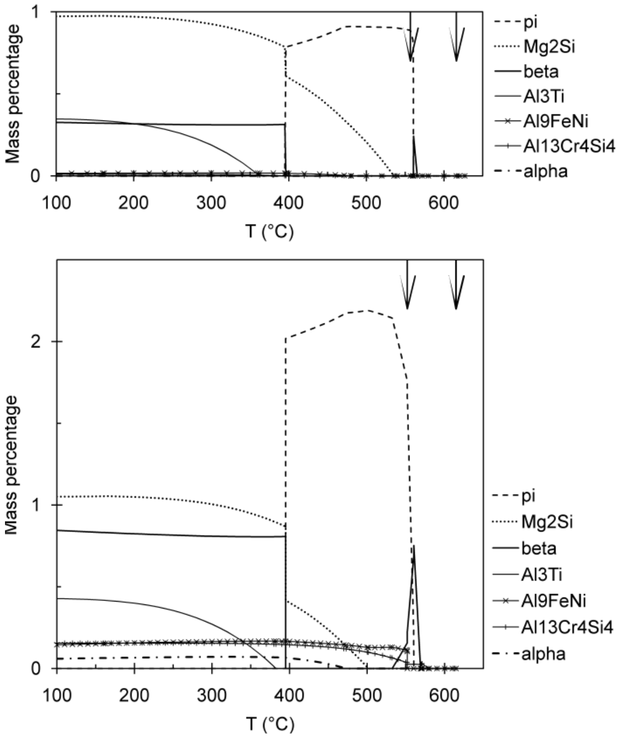

Fig.2 Calculated phase equilibria (minor phases) for Al alloys with compositions given in Table 1 corresponding to (a) batch 1 and (b) batch 2.

The tensile properties of T4 and T6 heat treated samples of batch 1 and batch 2 were determined and the results are shown in Table 2. It has been shown previously by the authors [3] that strong correlations exist between strength and Mg-content of these alloys (with other element contents kept constant). Therefore, the expectation is that batch 2 should give higher strength than batch 1 in both temper conditions (wt% Mg of 0.67 and 0.62% respectively – Table 1). However, from Table 2 it can be seen that the strength (yield strength and ultimate tensile strength of the two alloys are fairly similar). This can be related directly to the higher Fe-content of batch 2 compared to batch 1. The presence of high quantities of the Mg-containing π-phase in samples from batch 2 (Fig. 3(b)) causes a reduction in the amount of magnesium in solid solution [3]. This has a detrimental effect on the aging behavior of samples from this batch compared to batch 2 (less of the strengthening Mg_2Si precipitates can be formed during artificial aging). Note that the Mg-free particles such as β-Al_5FeSi and Al_9FeNi particles do not contribute to this effect.

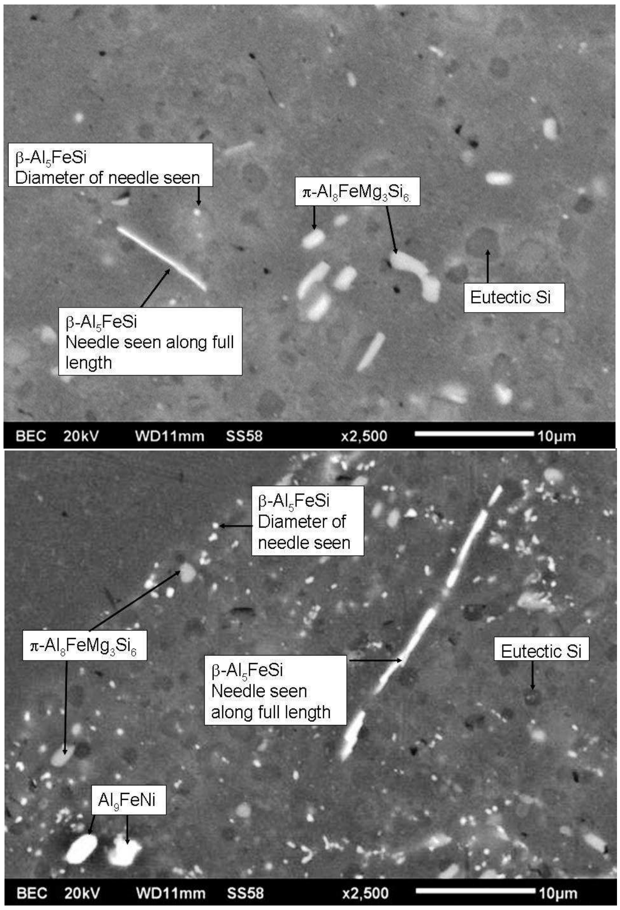

Fig.3 Backscattered electron images of T6 samples of (a) batch 1 and (b) batch 2.

Although Thermo-Calc (Fig. 2) also predicts low quantities of $Al_{13}Cr_4Si_4$, no such particles were observed with SEM in any of the samples.

Even though the yield and ultimate tensile strengths of samples from batch 1 and batch 2 are similar, the ductilities differ significantly (Table 2). The %elongation of samples from batch 2 is considerably lower than for samples from batch 1 in both temper conditions. Fig. 5 shows a backscattered electron image of a sample from batch 2 in the T6 condition after tensile testing. The fracture occurred to the right of the image and part of the fracture surface can be seen. Micro-cracking of the intermetallics can clearly be seen. Taylor and co-workers [9] also reasoned that any increase in the amount of hard, brittle π-intermetallics would lead to a decrease in elongation to fracture values in this alloy system. Finally, Yang and co-authors [10] showed the negative effects of Fe-intermetallics on the mechanical properties of Al-7Si-Mg alloys, especially the ductility.

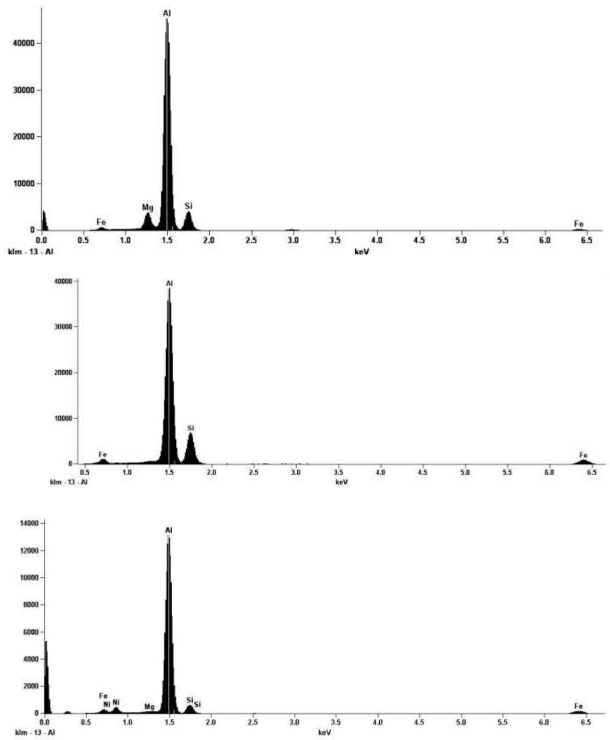

Fig.4 EDS spectra of qualitatively identified (a) π-$Al_8FeMg_3Si_6$, (b) β-Al_5FeSi (note the absence of a Mg-peak) and (c) Al_9FeNi particles (note the presence of a Ni-peak).

The quality index (QI) was used in this work to allow comparison of different compositions. The quality index relates the ductility (% elongation or %A) and strength (ultimate tensile strength or UTS) into a single term. It was originally developed by Drouzy and co-workers [11]. Caceres and co-authors [12] showed the fundamental basis of the quality index. The quality index (specifically for alloys A356/7) is given by equation 1:

QI (MPa) = UTS (MPa) + 150log(% elongation) (1)

The QI of batch 2 is appreciably lower than for batch 1 (Table 2). The UTS values for the two compositions are relatively similar in each temper condition, but the ductility of batch 2 is compromised by the presence of high volume fraction Fe-containing intermetallics (Fig. 5). This in turn results in a relatively poor QI being obtained for batch 2 in both the T4 and T6 temper conditions.

Another effect of the intermetallics in this alloy system (which was not studied in this work) is their influence on corrosion properties. Yang and co-workers [10] showed that intermetallic compounds play a major role in the pit initiation process of Al–7Si–Mg alloys. Micro-galvanic cells are produced, leading to corrosion attack along the interface between the intermetallic compounds and the aluminum alloy matrix. Not only does batch 2 have an inferior Quality Index compared to batch 1, but its corrosion resistance is also expected to be relatively poor.

Table 2 Yield strength (YS), ultimate tensile strength (UTS) and % elongation (%A) of T6 heat treated F357 samples. The standard deviation from five values for tensile properties is also indicated in brackets

Batch	YS (MPa)	UTS (MPa)	% A	QI (MPa)
T4 (540^oC-1h, 120 h natural aging)				
1	172 (4.7)	297 (4.0)	17 (2.5)	482
2	169 (3.6)	285 (5.7)	8.2 (2.0)	422
T6 (540^oC-1h, 20 h natural aging, 180^oC-4h artificial aging)				
1	312 (4.1)	355 (3.9)	6.0 (1.3)	472
2	313 (2.2)	353 (5.0)	3.5 (0.64)	435

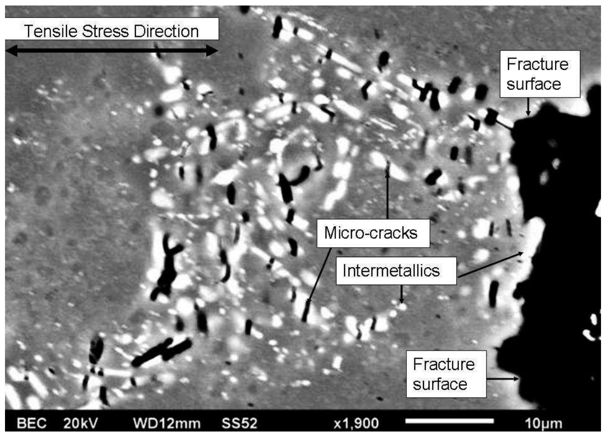

Fig.5 Backscattered electron image of T6 sample of batch 2 after tensile testing showing the fracture surface on the right, as well as micro-cracking of the intermetallics

4 Conclusions

1) Higher Fe and Ni contents in batch 2 of alloy F357 resulted in the formation of high volume fractions of intermetallics such as π-$Al_8FeMg_3Si_6$, β-Al_5FeSi and Al_9FeNi compared to batch 1. Although the Cr-content of batch 2 was an order of magnitude higher than for batch 1, no $Al_{13}Cr_4Si_4$ particles could be detected with SEM.

2) Even though the Mg-content of batch 2 is higher than for batch 1, similar yield strength and ultimate tensile strength were obtained in both the T4 and T6 temper conditions. This is due to the presence of high quantities of the Mg-containing π-phase in samples from

batch 2. The π-phase removes Mg from solid solution and therefore causes reduced precipitation of the strengthening Mg_2Si precipitates during artificial aging.

3) Micro-cracking of the intermetallics occurred during tensile testing. This caused a marked reduction in ductility of batch 2 compared to batch 1. As a consequence, the Quality Index of batch 2 is also decreased compared to batch 1.

References

[1] LIU D, ATKINSON H V, KAPRANOS P, JIRATTITICHAROEAN W, JONES H. Microstructural evolution and tensile mechanical properties of thixoformed high performance aluminium alloys [J]. Materials Science and Engineering A, 2003, 361: 213−24.

[2] ASM SPECIALITY HANDBOOK: Aluminium and Aluminium Alloys [M]. Materials Park, Ohio, ASM International, 1993: 718.

[3] MöLLER H, GOVENDER G, STUMPF W E, PISTORIUS P C, Comparison of heat treatment response of semisolid metal processed alloys A356 and F357 [J]. International Journal of Cast Metals Research, 2010, 23(1): 37−43.

[4] IVANCHEV L, WILKINS D, GOVENDER G. Paper 152 [C]//8th International Conference on Semi-solid Processing of Alloys and Composites. Limassol, Cyprus, 2004.

[5] ANDERSSON J O, HELANDER T, HOGLUND L, SHI PF, SUNDMAN B. Thermo-Calc & DICTRA, computational tools for materials science [J]. Calphad, 2002, 26: 273−312.

[6] MöLLER H, GOVENDER G, STUMPF W E, KNUTSEN R D. Influence of temper condition on microstructure and mechanical properties of semisolid metal processed Al-Si-Mg alloy A356 [J]. International Journal of Cast Metals Research, 2009, 22(6): 417−21.

[7] ZOLOTOREVSKY V S, BELOV N A, GLAZOFF M V. Casting Aluminum Alloys [M]. Amsterdam: Elsevier Publishers, 2007: 79.

[8] CHEN C-L, THOMSON R C. The combined use of EBSD and EDX analyses for the identification of complex intermetallic phases in multicomponent Al-Si piston alloys [J]. Journal of Alloys and Compounds, 2010, 490: 293−300.

[9] TAYLOR J A, STJOHN D H, ZHENG L H, EDWARDS G A, BARRESI J, COUPER M J. Solution treatment effects in Al-Si-Mg casting alloys, Part 1 [J]. Aluminum Transactions, 2001, 4-5: 95-110.

[10] YANG C-Y, LEE S-L, LEE C-K, LIN J-C. Effects of Be and Fe on the mechanical and corrosion behaviors of A357 alloys [J]. Materials Chemistry and Physics, 2005, 93: 412−19.

[11] DROUZY M, JACOB S, RICHARD M. Interpretation of tensile results by means of quality index and probable yield strength [J]. International Cast Metals Research Journal, 1980, 5(2): 43-50.

[12] CACERES C H, MAKHLOUF M, APELIAN D, SIGWORTH G. Quality index chart for different alloys and temperatures: A case study on aluminium die-casting alloys [J]. Journal of Light Metals, 2001, 1(1): 51−59.