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

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Abstract: The microstructures and tensile properties of semi-solid metal high pressure die cast (SSM-HPDC) F357 alloys with low and high levels of Fe, Ni and Cr were compared in different temper conditions. ThermoCalc software was used to predict the different intermetallics that can be expected in the alloys, and scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) was used to investigate the actual intermetallics that formed. The influence of these intermetallics on tensile properties was quantified. The results show that lower strength is obtained in the alloy with high Fe, Ni and Cr levels. This is attributed mainly to the formation of more π-$Al_8FeMg_3Si_6$ phase, which removes strengthening Mg atoms from solid solution. Also, the ductility of the high Fe, Ni and Cr levels 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 results in a decrease of the quality index of this alloy compared with the alloy with low levels of Fe, Ni and Cr.

Key words: 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% 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 influences 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 elements are allowed to a maximum of 0.05%.

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

2 Experimental

Semi-solid metal slurries of alloy F357 were prepared using the CSIR rheocasting process[4]. Chemical composition of prepared alloy F357 is given in Table 1. Plates (4 mm×80 mm×100 mm) were cast in steel moulds with a 130 t high pressure die casting machine. The levels of Fe, Ni and Cr of batch 1 were well within the limits of the specification (shown in Table 1). The high levels of Fe, Ni and Cr in plates of

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Table 1 Chemical composition limits for alloy F357[2], as well as compositions of alloys used in this study(mass percentage,%)

		Si	Mg	Fe	Cu	Mn	Zn	Ti	Other element (Each)	Other element (Total)
Specification	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	

batch 2 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%), their quantities are an order of magnitude greater than for batch 1.

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 12.5 mm. To determine the 0.2% proof stress, a stress rate of 10 MPa/s was used and for the ultimate tensile stress determination a displacement rate of 10 mm/min was used. 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 were 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 d) 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 used in this study were based on cycles determined by the authors in previous work[3,6].

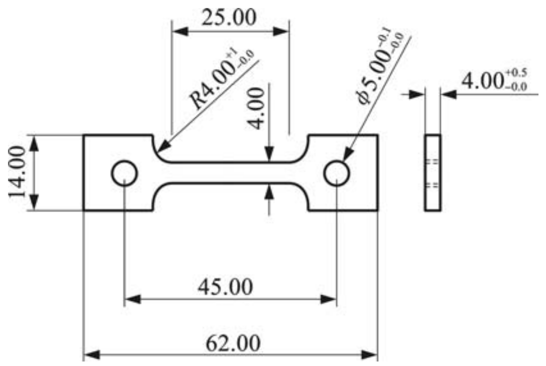

Fig.1 Dimensions of tensile samples used in this study (Unit: mm)

3 Results and discussion

The calculated phase equilibria (minor phases) for the Al alloys used in this study (Table 1) are shown in Fig.2, where the liquidus and solidus temperatures are indicated by arrows and α 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).

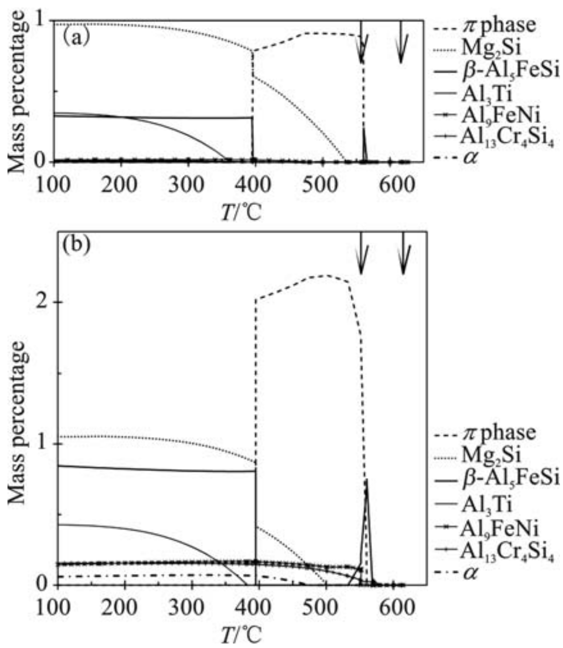

Fig.2 Calculated phase equilibria (minor phases) for Al alloys: (a) Batch 1; (b) Batch 2

From Fig.2, it is seen that the predicted Mg_2Si content is slightly lower for batch 1 than batch 2 because the Mg-content of batch 1 is lower than that of batch 2. 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.

Scanning electron microscopy (coupled with EDS to tentatively identify phases) was used to study the intermetallic phases of alloys 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-$Al_8FeMg_3Si_6$ can 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 can also be identified (Fig.3(b) and Fig.4(c)). Note that Si is 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].

The tensile properties of T4 and T6 heat treated samples of batch 1 and batch 2 were determined and the results are listed 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 (Mg content of 0.67% and 0.62% respectively as listed in Table 1). However, from Table 2 it can be seen that the 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 with 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 with batch 1 (less 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.

Although Thermo-Calc (Fig.2) also predicts low quantities of $Al_{13}Cr_4Si_4$, no such particle is 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

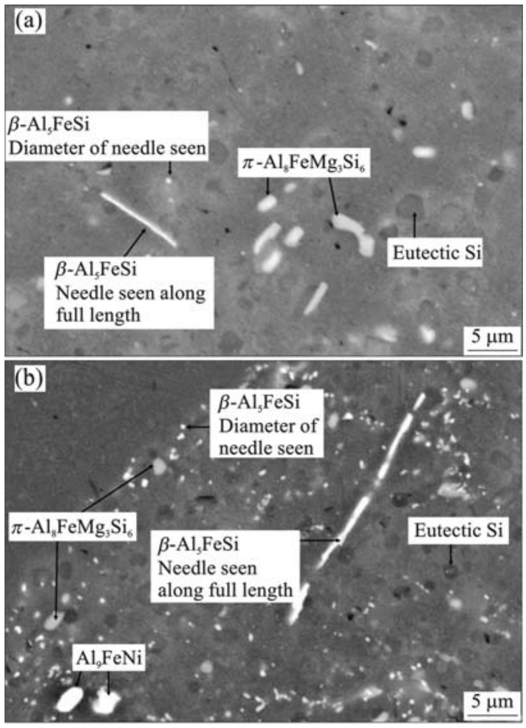

Fig.3 Backscattered electron images of T6 samples: (a) Batch 1; (b) Batch 2

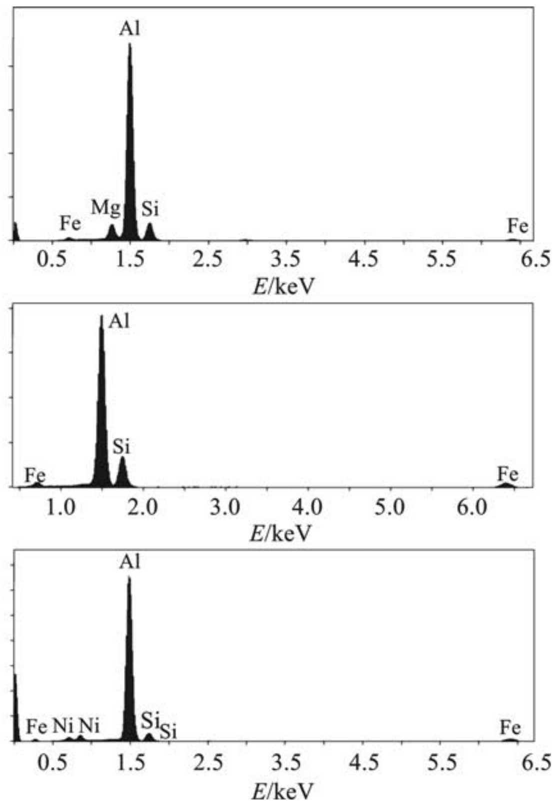

Fig.4 EDS spectra of qualitatively identified (a) π-$Al_8FeMg_3Si_6$, (b) β-Al_5FeSi (note absence of a Mg-peak) and (c) Al_9FeNi particles (note presence of a Ni-peak)

of samples from batch 2 is considerably lower than that of 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 be clearly seen. TAYLOR et al[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 et al[10] showed the negative effects of Fe-intermetallics on the mechanical properties of Al-7Si-Mg alloys, especially the ductility.

Table 2 Yield strength, ultimate tensile strength and elongation of T6 heat treated F357 samples

Heat treat	Batch	Yield strength /MPa	Ultimate Tensile Strength /MPa	Elongation /%	Quality index /MPa
T_4	1	172 (4.7)	297 (4.0)	17 (2.5)	482
	2	169 (3.6)	285 (5.7)	8.2 (2.0)	422
T_6	1	312 (4.1)	355 (3.9)	6.0 (1.3)	472
	2	313 (2.2)	353 (5.0)	3.5 (0.64)	435

Note: T4 (540 °C /1h, natural aging for120 h); T6 (540 °C /1h, natural aging for 20 h, 180 °C /4h, artificial aging) ;standard deviation from five values for tensile properties is also indicated in brackets

The quality index was used in this work to allow comparison of different compositions. The quality index relates the ductility (elongation) and ultimate tensile strength into a single term. It was originally developed by DROUZY et al[11]. CACERES et al[12] showed the fundamental basis of the quality index. The quality index (specifically for alloys A356/7) is given by Eq.1:

$$I=\sigma+150\lg y \quad (1)$$

where I is the quality index, MPa; σ is ultimate tensile strength, MPa; y is the elongation, %.

The quality index of batch 2 is appreciably lower than that of batch 1 (Table 2). The ultimate tensile strengths 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 quality index 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 et al[10] showed that intermetallic compounds played a major role in the pit initiation process of Al–7Si–Mg alloys. Micro-galvanic cells are produced, leading to corrosion

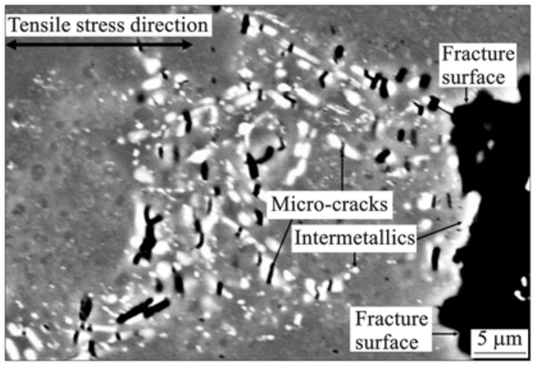

Fig.5 Backscattered electron image of T6 sample of batch 2 after tensile testing showing fracture surface on right, as well as micro-cracking of intermetallics

attack along the interface between the intermetallic compounds and the aluminum alloy matrix. Not only does batch 2 have an inferior quality index compared with batch 1, but its corrosion resistance is also expected to be relatively poor.

4 Conclusions

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

2) Even though the Mg-content of batch 2 is higher than that of batch 1, similar yield strength and ultimate tensile strength are obtained in both 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 occurs during tensile testing. This causes a marked reduction in ductility of batch 2 compared with batch 1. As a consequence, the quality index of batch 2 is also less than that of batch 1.

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