DEVELOPMENT OF A NEW Al-Fe-Ni ALLOY FOR ELECTRIC VEHICLE APPLICATIONS

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Abstract

The electrification of automotive is growing rapidly, resulting in an increased need for aluminum alloys with high electrical conductivity. The core element of the electric vehicle, besides the batteries, is an electric motor, which replaces the internal combustion engines of a traditional gasoline vehicle. These applications require both high strength and high electrical conductivity. This paper presents the development of a new Al-Fe-Ni aluminum alloy that provides a good combination of mechanical properties and electrical conductivity. The alloy is well suited for high-pressure vacuum die casting (HPVDC). The as-cast microstructures, mechanical properties and electrical conductivity were studied for alloys with different Fe/Ni combination. The relationship between the microstructure and properties is analyzed, and the strengthening mechanisms of the studied alloy are discussed. Based on the experimental results, the new alloy demonstrates excellent potential for electric vehicle applications produced by high-pressure vacuum die casting.

Keywords: *aluminum foundry alloys, mechanical properties, electrical conductivity, electric motor*

Introduction

The significant growth of electrical vehicles (EV) presents major opportunities for material suppliers. The core element of the EV, apart from electric vehicle batteries, is an electric motor, which replaces the internal combustion engines. The growing EV market needs more alloys for electric motor components.[1] Meanwhile, applications such as heat dissipation parts for thermal management also require alloys with high electrical conductivity (thermal conductivity) and high strength.

The 1XX foundry alloys for electrical applications were widely used in magnetic electric motors. 1xx series alloys have excellent electrical conductivity (50-60 %IACS) but with very poor yield strength (25-50 MPa). On the contrary, structural alloys such as A365.1 provide high yield strength (up to 200 MPa) but poor electrical conductivity (<40 %IACS). For electrical vehicle components, such as a rotor or an inverter, both high strength and high electrical conductivity are desired.[2,3]

In the past, AlFe0.35Ni5.3 alloy was developed for rotor applications.[3] The AlFe0.35Ni5.3 alloy demonstrates good yield strength and electrical conductivity in as-cast condition. However, this alloy requires a long alloying cycle time due to its high Ni content. In addition, nickel is an expensive component of this alloy. It is therefore desirable to obtain comparable or improved mechanical and electrical properties while having nickel as an addition and not a major component (i.e., limiting the amount of nickel included). A 6xxx type alloy was developed to reduce the nickel content by adding silicon and magnesium.[4] The properties are shown in Figure 1. The new 6xxx +Ni alloy provides a range of strength and electrical conductivity not yet achieved by previous alloy systems. However, a T6 heat treatment was needed to obtain peak properties.

The objective of this project is thus to develop a low-cost solution for electric vehicle applications in the as-cast temper. In this study, the effect of Fe and Ni combination

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on the mechanical and electrical properties of Al-Fe-Ni alloy was studied. CALculation of PHAse Diagrams (CALPHAD) methodology was applied to predict the phase transformation with different Ni contents. High-pressure vacuum die casting (HPVDC) was used to produce the samples to evaluate the mechanical properties and electrical conductivity.

Design of Experiments

The chemical compositions of the designed alloys were determined using optical emission spectroscopy (OES), and the results are shown in Table 1. The alloys were melted in a 300-kg electric resistance furnace. In order to remove the detrimental impact of unwanted impurities on electrical conductivity, a boron treatment was performed using Al-8%B. An amount of about 0.4 kg Al-8%B master alloy was added during alloy melting process. AlFe1.7 and AlNi6 alloys were cast as reference alloys.

HPVDC experimental plates were produced using the Bühler Evolution 26D vacuum die casting machine from the Centre de Metallurgie du Quebec (CMQ). The vacuum level in the die cavity was set at 750 mbar to minimize entrapped air. The test plate dimensions were 220 mm long, 65 mm wide and 3 mm thick, as shown in Figure 2. The die was pre-heated to 210 °C, while the shot sleeve temperature was set to 300 °C. The molten metal temperature of 750 °C was used to minimize the formation of externally solidified crystals (ESCs).

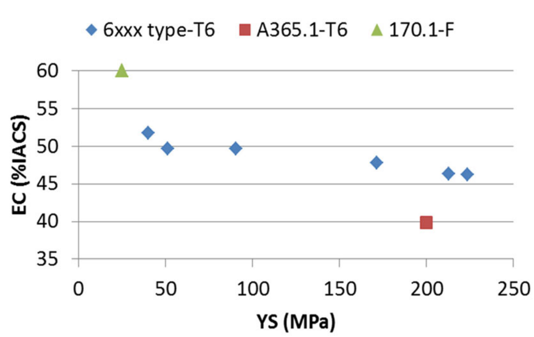

Figure 1. Property of 6xxx type alloy compared with A365.1 and 170.1.[4]

HPVDC plates were water quenched immediately after demolding. Samples for tensile tests were cut from casting blanks (the middle rectangle part, as shown in Figure 2). The plates were then machined into the form of test samples with precise dimensions according to ASTM B557 standards, as shown in Figure 3. For each condition, ten tensile samples were pulled.

The electrical conductivity of the plates was measured at room temperature using a Sigmatest 2.069 edge current portable electrical conductivity meter. Nine different locations were measured on each sample. The average value of these measurements was calculated.

Metallographic samples were also taken from the as-cast plates. Optical microscopy and scanning electron microscopy (SEM) were used to analyze the as-cast microstructure and to identify the intermetallic phases.

Thermodynamic calculations were performed using Thermo-Calc 2020a with a TCAL database (TCS Al Alloys

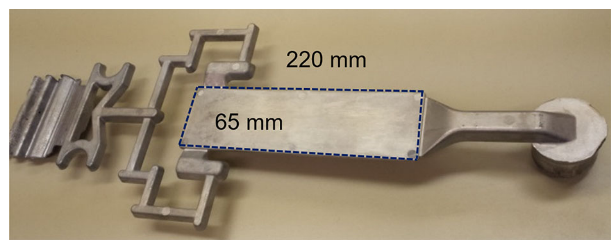

Figure 2. Experimental HPVDC plate.

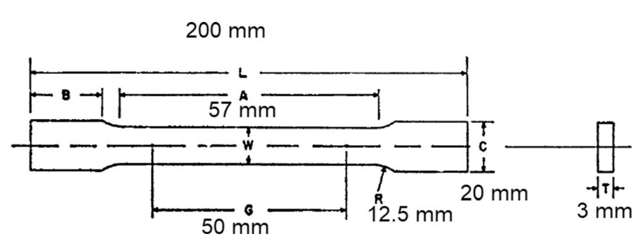

Figure 3. ASTM B557 tensile test specimen dimensions.

Table 1. Chemistry of the Tested Alloys with Different Amounts of Nickel (wt.%)

Alloys	Si	Fe	Ni	Mn	Cr	Ti	V
AlFe1.7	0.05	1.53	–	0.0067	0.0016	0.0096	0.0115
AlFe1.7Ni1	0.05	1.79	1.0	0.011	0.0007	0.0008	0.0039
AlFe1.7Ni2	0.06	1.80	2.1	0.011	0.0007	0.0008	0.0039
AlFe1.7Ni4	0.07	1.76	4.0	0.011	0.0007	0.0008	0.0039
AlNi6	0.05	0.1	5.8	<0.01	0.0006	0.08	0.01

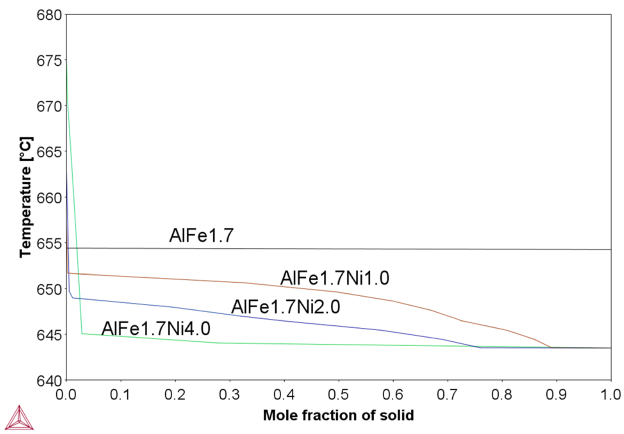

Figure 4. Scheil calculation on the alloys showing the effect of Ni on solidification.

database v3.0) in this study. The phase mole fraction under Scheil condition was calculated to predict non-equilibrium solidification. Scheil model assumes that there is no diffusion in the solid phase and infinitely fast diffusion of all elements in the liquid phase. This calculation provides a good approximation for the solidification processes with high cooling rates in high-pressure die casting.

Results and Discussion

The constituent phase formation was simulated to numerically estimate the mole percentage of solid phases formed during solidification by the Thermo-Calc Scheil model. The impact of Ni addition on solidification and changes in mole percentages of the main solid phase during the rapid cooling of the alloys are presented in Figure 4 and Table 2. It is noted that addition of Ni in AlFe1.7 alloy obviously decreased the eutectic reaction temperature. The mole fraction of the solid phases changed with the change of chemical composition in the alloys. In AlFe1.7 alloy, $Al_{13}Fe_4$ eutectic phases were formed during solidification. Addition of Ni promotes Al_9FeNi and Al_3Ni phase formation during solidification. The mole fraction of $Al_{13}Fe_4$ phase is decreased, while the mole fraction of Al_9FeNi and Al_3Ni phase is increased with increasing amount of Ni in the alloys.

Figure 5 shows the as-cast microstructure of the alloys. The AlFe1.7 binary alloy exhibited Al-Fe eutectic phases during solidification along the interdendritic boundary. Adding 1% Ni to the AlFe1.7 alloy promoted both the coarse primary AlFeNi phases and the fine AlFeNi eutectic phase. The exact phase type was remained unexplored by the current results. Further analysis is recommended. The eutectic phase appeared more uniformly distributed in the AlFe1.7Ni alloys than the Al-Fe eutectic phases. The AlFe1.7Ni2 alloy exhibits a similar microstructure to that of the AlFe1.7Ni1 alloy. Further increasing Ni to 4% in

Table 2. Phase of the Alloys with Various Ni Amounts (Scheil Calculation, mol.%)

Phases	AlFe1.7	AlFe1.7Ni1 (%)	AlFe1.7Ni2 (%)	AlFe1.7Ni4 (%)
$Al_{13}Fe_4$	3.4%	2.8	1.7	0.2
Al_9FeNi	–	2.0	4.8	8.9
Al_3Ni	–	0.6	1.4	3.7
Total	3.4%	5.4	7.9	12.8

AlFe1.7Ni4 alloy significantly increased the amount of large AlFeNi intermetallics.

Table 3 summarizes the mechanical properties and electrical conductivity of the tested alloys in the as-cast condition. Figure 6 presents the effect of Ni on yield strength and electrical conductivity in AlFe1.7-Ni alloys. The addition of Ni to the AlFe1.7 alloys significantly improved strength. Yield strength increased from 51.0 to 67.2 MPa by adding 1% Ni. Electrical conductivity was surprisingly increased from 50.5 to 53.4 %IACS. Further increasing Ni from 1 to 2 % slightly increased the yield strength from 67.2 to 71.0 MPa, while the effect on electrical conductivity was negligible. Increasing Ni from 2 to 4% significantly decreased electrical conductivity from 53.6 to 51.7 %IACS and slightly increased the yield strength from 71 to 72.7 MPa. The increase in electrical conductivity with the addition of Ni in AlFe1.7-Ni alloys is probably due to the formation of Al_9FeNi eutectic phases that consume Fe and Ni elements and reduce the supersaturation of Fe and Ni in aluminum matrix during solidification. Further studies are needed to validate the assumption and to better understand the mechanism behind this phenomenon.

Figure 7 summarizes the Thermo-Calc calculation results of temperature as a function of solid fraction for various alloys. Hot tearing was predicted to occur in the late stages of solidification at the interdendritic boundaries. The greater the temperature change during the later stages of solidification, the greater the probability of causing hot tearing. As shown in Figure 7, alloys containing 1.7% Fe and Ni exhibit a low temperature dependence on the solid fraction in the 80-100% solid region and thus less probability of experiencing tearing. These alloys are expected to have hot tearing resistance similar to that of AlFe1.7 alloy and the high Ni containing AlNi6 binary alloys.

Kou[5] proposed an index criterion which is the slope of T vs $f_s^{1/2}$ ($\Delta T/\sqrt{fs}$) to differentiate hot tearing. The steeper the solidification curve slope ($\Delta T/\sqrt{fs}$) in the critical solid fraction zone ($0.87<f_s<0.94$), the higher the hot tearing sensitivity. Figure 8 shows the results of the hot tearing index ($\Delta T/\sqrt{fs}$) for the alloys. The hot tearing index of A356 was calculated as a reference. Alloys containing

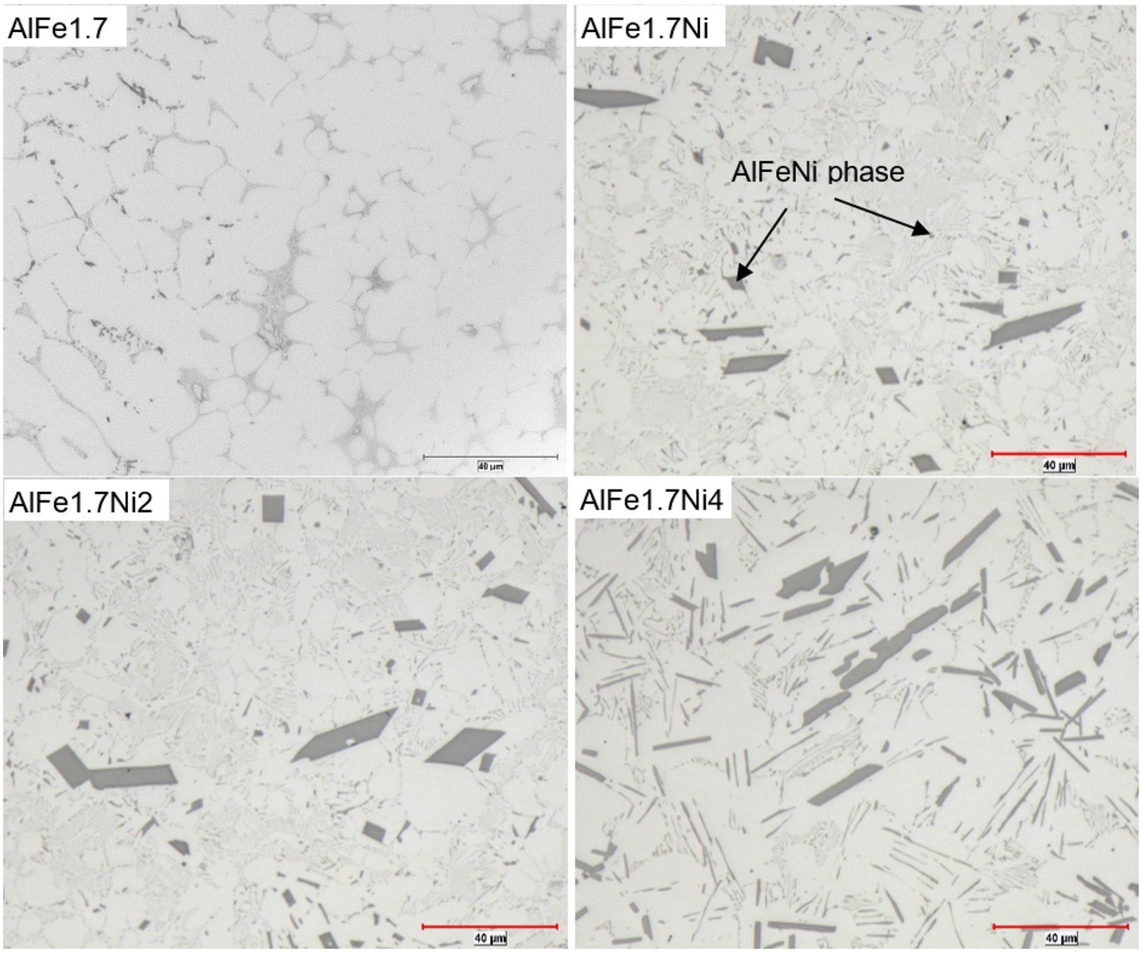

Figure 5. Typical as-cast microstructure of the tested alloys.

Table 3. Mechanical Properties and Electrical Conductivity of Al-Fe-Ni Alloys

Alloy	UTS (MPa)	YS (MPa)	El%	EC (%IACS)
AlFe1.7	132.8	51.0	25.0	50.5 ± 0.53
AlFe1.7Ni1	155.3	67.2	19.2	53.4 ± 0.44
AlFe1.7Ni2	163.5	71	12.3	53.6 ± 0.37
AlFe1.7Ni4	151.5	72.7	5.0	51.7 ± 0.65

1.7% Fe and Ni exhibit a very low hot tearing index of ≤ 13, similar to that of AlFe1.7 and AlNi6, indicating the low probability of experiencing hot tearing. All the studied alloys are not expected to experience tearing issues during production.

Figure 9 shows the property comparison of the new developed alloy with other commercial electric alloys. Compared to the electrically conductive AlFe0.8 alloy, the AlFe1.7Ni and AlFe1.7Ni2 alloys demonstrate better yield strength with a slight decrease in electrical conductivity. The AlFe1.7Ni alloy showed the best combination of properties and cost (due to low Ni content of 1 wt. % and

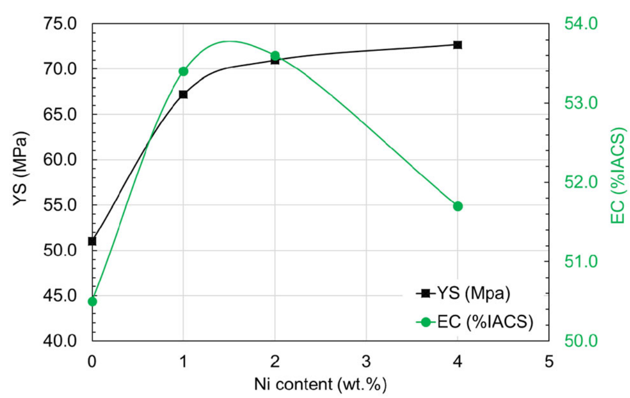

Figure 6. Yield strength and electrical conductivity of AlFe1.7-Ni alloys showing the effect of Ni.

Ni being a costly component). This alloy is therefore recommended for applications that require strength and electrical conductivity.

Conclusions

- AlFe1.7-Ni variants demonstrated a combination of high electrical conductivity and intermediate

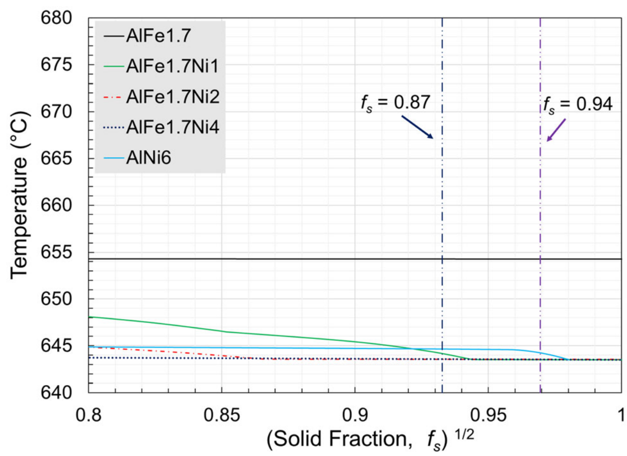

Figure 7. Temperature as a function of (solid mole fraction, f_s)$^{1/2}$ for different alloys.

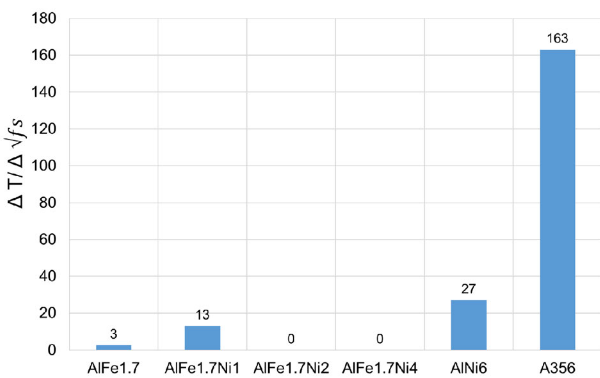

Figure 8. Hot tearing prediction using Thermo-Calc calculation.

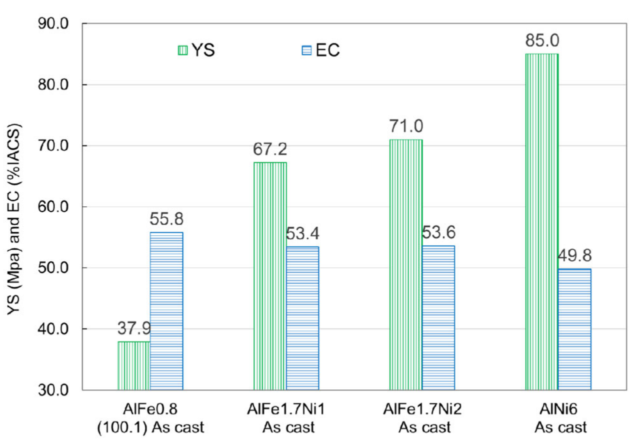

Figure 9. Property comparison for the new alloys with commercial electrical conductor alloys.

yield strength that could potentially be applied for electrical conductors in the as-cast condition.

- Adding Ni up to 2% in AlFe1.7 alloys increased both the yield strength (20 MPa) and electrical conductivity (3 %IACS).
- Increasing Ni from 2% to 4% slightly increased the yield strength (1.6 MPa) while decreasing the electrical conductivity (1.9 %IACS).
- AlFe1.7-Ni variants show an excellent hot tearing index.

Acknowledgements

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