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This paper compares the castability of the near eutectic aluminum-cerium alloy system to the aluminum-silicon and aluminum-copper systems. The alloys are compared based on die filling capability, feeding characteristics and tendency to hot tear in both sand cast and permanent mold applications. The castability ranking of the binary Al–Ce systems is as good as the aluminum-silicon system with some deterioration as additional alloying elements are added. In alloy systems that use cerium in combination with common aluminum alloying elements such as silicon, magnesium and/or copper, the casting characteristics are generally better than the aluminum-copper system. In general, production systems for melting, de-gassing and other processing of aluminum-silicon or aluminum-copper alloys can be used without modification for conventional casting of aluminum-cerium alloys.

Introduction

A new alloy system has been developed that uses cerium as a primary alloying element at near eutectic compositions. Additional alloying elements are used, primarily to assist in the development of room temperature mechanical properties. The cerium in the alloys forms a primary intermetallic (Al11Ce3) phase in the Al-rich region of the Al–Ce system, which provides for excellent retention of mechanical strength and ductility at high temperatures (200–400 °C). A detailed description of the microstructure present in the alloy systems can be found in Ref. [1]. Despite their exceptional mechanical properties, the use of high performance alloys in high volume production has been somewhat restricted by concerns about their casting characteristics. The casting characteristics of greatest concern are resistance to hot tearing and adequate fluidity, or mold filling capability. Good fluidity and hot tear resistance are particularly important in higher production casting processes, such as permanent mold or high pressure die casting.

Aluminum alloys that perform well at temperatures of up to 200 °C typically include copper, nickel or a combination of the two, along with alloying elements that have other functions, such as improving heat treat response or grain refining. Typical chemistries of a number of high performance alloys are shown in Table 1. All compositions are weight percentages of the alloying element.

The addition of copper and magnesium improves strength and hardness at elevated temperatures, while nickel is also added to aluminum-copper and aluminum-silicon alloys to improve hardness and strength at elevated temperature and to reduce the coefficient of thermal expansion. The solid solubility of nickel in aluminum does not exceed 0.04%, so it is present as an intermetallic, often in combination with iron. Additionally, silicon is used to reduce hot shortness and to improve the fluidity of the alloys [2].

The Aluminum Association comparatively rates alloys on a scale from 1 to 5 in decreasing order of performance [3]. Those alloys that contain high amounts of copper with little silicon are generally rated a 3, or average, for fluidity and a 4, or below average, for resistance to hot cracking. Alloy 336 is rated a 1, or excellent, for fluidity because of the high amounts of silicon in the alloy. The most common cast alloys such as 356, 357, and 355 all rank excellent for both fluidity and resistance to hot cracking.

Producing a casting in an alloy that is difficult to cast raises its cost regardless of alloy cost. As a consequence, the easier-to-cast alloys are most often specified in spite of the fact that they are less suitable for some aspects of the product, or ferrous alloys are used because of their excellent high temperature properties, resulting in heavier, less efficient structure.

Experimental

Initial analysis of the Al–Ce system produced via a powder metallurgy followed by hot forging showed promising strengths at temperatures up to 343 °C [4]. A review of the phase diagram showed a promising eutectic composition at around 10 wt% cerium that suggested the alloy could be cast. Figure 1 depicts the Thermo-Calc calculated binary phase diagram of Al–Ce system. Casting trials were performed using a permanent mold that contained the standard ASTM B108 test bar geometry. This mold was heated using electrical cartridge heaters, which maintain the minimum set-point temperatures to within 10 °C. The casting alloys were prepared in 25 kg batches using P1520 ingot with the composition shown in Table 2. Melting was done under nitrogen cover gas. Commercial cerium metal (Molycorp) with >99% purity was added to achieve binary compositions of 6, 8, 10, 12 and 16% cerium. The alloy was not degassed and was poured into the mold heated to 400 °C using a casting temperature of 750°.

When casting alloys containing 6% silicon or more at the indicated mold and metal temperatures, the test bar set easily fills and good test bars are produced. Alloys containing less silicon require additional superheat to either the mold or the metal to fill consistently. At compositions up to 10% cerium, the mold filled completely and the production of sound bars was consistent with those produced with alloys containing 6% Si. At 12% cerium, mold filling capability declined and the metal temperature was adjusted upwards by 25 °C to achieve complete fill. Figure 2 shows that at 16% cerium, the mold did not fill completely at a mold temperature of 425 °C and a casting temperature of 775 °C. The incomplete mold filling is due to the rapidly increasing melting temperature above the eutectic point for the alloy. It should be noted that none of the test bars showed any evidence of hot tearing.

A second trial was conducted using the same materials and processing parameters, but utilizing a step plate mold and a hot tearing mold to estimate feeding characteristics and susceptibility to hot tearing. Images of castings produced are shown in Figs. 3 and 4. Overall castability of the studied compositions appears to be in line with currently available commercial alloys. As a comparison, hot-tear molds and step-plates were cast from A206. From observations of A206 versus identical casting of Al–Ce alloy, A206 appears to have larger and more pronounced macroscopic defects present than did the castings of Al–Ce alloys.

In general, Al–Ce alloys near the eutectic composition had good to excellent casting characteristics. However, the room temperature mechanical properties were not high enough for many commercial applications nor did the alloys have a positive response to heat treatment. See Table 3. The T6 cycle given was 538 °C for 90 min, quenched in H2O, and then aged at 154 °C for 3 h. Twenty additional alloys were produced using Al–8Ce as a base composition with additives of Si, Mg, Cu, Zn, Ni, Ti, Mn or Fe. Except for Mg, the addition of these alloying elements in excess of 1% reduced die filling capability even though many of the alloys had improved mechanical properties. For ternary Al–Ce–Mg alloys yield strength increased with increasing magnesium levels without a noticeable reduction in castability up to the tested level of 10% magnesium. Mechanical properties for three of these alloys is shown in Table 4.

Pilot Production

Since the Al–Ce–Mg alloys have both good castability and good mechanical properties, a 320 kg heat of an Al–10Mg– 8Ce alloy was produced to determine suitability of standard foundry processing parameters on metal quality and mechanical properties. Aluminum 535 was used as the base material with a chemistry as shown in Table 5. The ingot was weighed and melted and an additional 3.15 wt% magnesium was added and stirred into the melt using a rotary impeller running at 180 rpm and the pre-cerium chemistry was evaluated. Slightly more than 10% of the added magnesium was lost during the alloying process. Additional magnesium was added with the cerium for a final magnesium composition of 10.09% and a calculated cerium content of 8.01%. No grain refiners were used. The alloy was degassed using 5% SF6 in nitrogen for 40 minutes to a density of 2.49 g/cm3. High magnesium alloys can be difficult to degas, often requiring multiple degassing cycles to achieve specified gas levels. Sigworth describes an alloy correction factor that can be utilized to quantify the effects of alloying elements on hydrogen solubility of the melts and estimated degassing times [5]. For example, 356 has a correction factor (C) of 0.67 and 535 has a correction factor of 1.18. The authors are unaware of published correction factors for 10% magnesium but the hydrogen solubility is very high (see Fig. 5) compared to other commercial alloys and C would be expected to be higher. According to Sigworth, the rate of hydrogen removal is proportional to C2. While there are no published correction factors for Ce, the success of a standard degassing time implies that Ce will reduce hydrogen solubility and therefore decrease the correction factor when compared to high magnesium alloys. A number of commercial castings were poured using patterns and permanent molds that were gated for 200 and 300 series alloys and are shown in Figs. 6 and 7. The gating was not modified to pour the Al–Ce. The casting quality was acceptable and equivalent to that produced in the production alloys. Test bars were produced from the production batch of material and tested to determine if the properties met those of the smaller batches of experimental material. The tensile strength from the pilot production was 3.5% higher than the experimental heats. Examination of test bars revealed lower oxide levels than previously produced. A total of 20 tensile bars from the pilot production lot have been tested at room temperature with properties of 235 ± 2 MPa tensile, 192 ± 4 MPa yield and 1% elongation. 250 kg of alloy was held for 17 h at 750 °C. The magnesium chemistry was checked at 9.78% or a 3.1% loss over that interval. This is a smaller than expected magnesium loss given the holding time and the lack of a protective atmosphere. The reasons for this unusual magnesium stability is being investigated.

Conclusions

A number of test pieces and complicated castings have been produced in the Al–Ce alloy systems. All of the data and experience to date indicate that Al–Ce or Al–Ce–Mg have castability equivalent to 300 series alloys. Other alloy additions have generally diminished castability but show promise with additional work. The use of production processing equipment resulted in better mechanical properties than the earlier development heats because of the more effective removal of oxides. Unexpected results that require further study include the apparent reduced solubility of hydrogen in alloys containing cerium and the role of cerium on the stabilization of magnesium in Al–Mg–Ce alloys.

Acknowledgements

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Table 1: Weight percent chemistry of some high performance aluminum alloys

	Cu	Mn	Mg	Ti	Si	Ni
A206	4.2–5	0 0.20–0.50	0.15–0.35	0.15–0.30	0.05 max	0.05 max
242	3.5–4.5	0.35 max	1.2–1.8	0.25 max	0.7 max	1.7–2.3
336	0.50—1.5	0.35	0.7-1.3	0.25 max	11–13	2.0–3.0

Table 2: Weight chemistry percent of the base alloy used in this study

	Si	Fe	Total Others	Aluminum
P1520	0.11	0.17	0.09	Remainder

Table 3: Room temperature mechanical properties (MPa) of binary Al-Ce alloys.

	Tensile, as cast	Yield, as cast	% E, as cast	Tensile, T6	Yield, T6	% E, T6
Al–16Ce	144	68	2.5	118	78	3.5
Al–12Ce	163	58	13.5	132	48	26.5
Al–10Ce	152	Test Error	8	129	46	24.0
Al–8Ce	148	Test Error	19	122	59	26.6
Al–6Ce	103	30	25	103	33	33.5

Table 4: Room and elevated temperature mechanical properties (MPa) of ternary Al-Ce-Mg alloys

	Tensile	Yield	%E	Tensile 260 °C	Yield 260 °C	%E 260 °C
Al–8Ce–4Mg	189	107	3	Not Tested		
Al–8Ce–7Mg	195	151	2	134	121	4
Al–8Ce–10Mg	227	186	1	137	130	4

Table 5: Starting composition of alloy 535 before magnesium and cerium additions.

	Si	Fe	Cu	Mn	Mg	Ti
535	0.098	0.091	0.041	0.159	6.85	0.016

Figure 1: Binary aluminum-cerium phase diagram as calculated using Thermo-Calc.

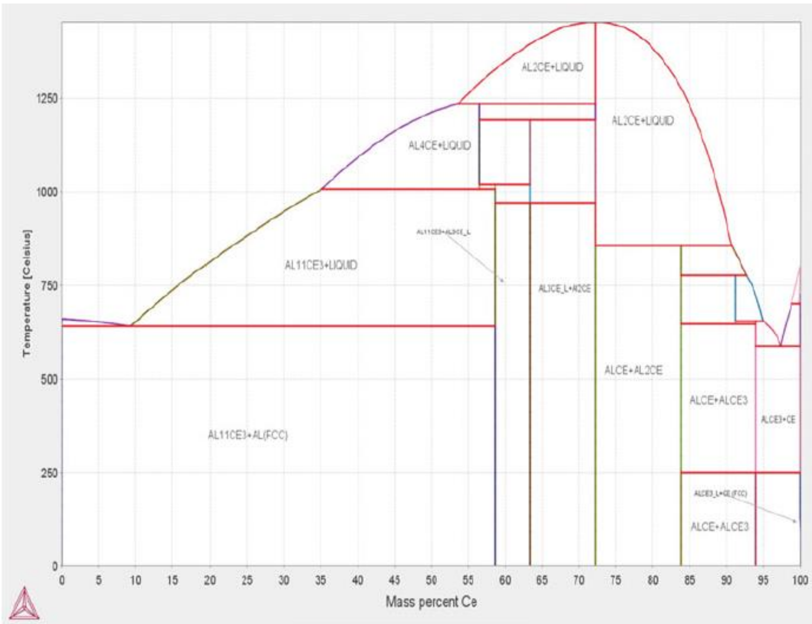

Figure 2: Partial fill test bar mold with Al-16Ce

Figure 3: X-Ray image of hot tear castings produced in Al-8Ce alloy.

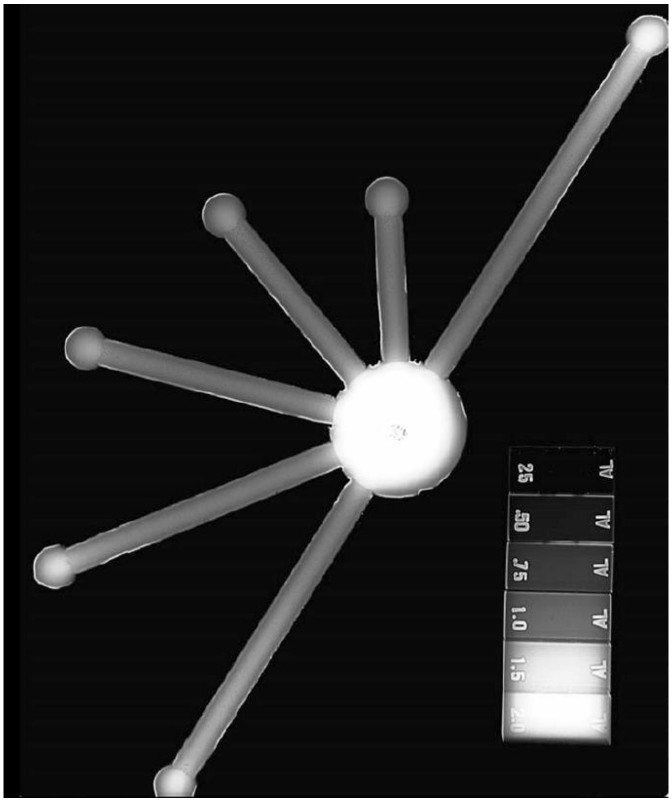

Figure 4: X-Ray image of step castings produced in Al-8Ce aooly. The right hand image was made from a casting using a copper chill.

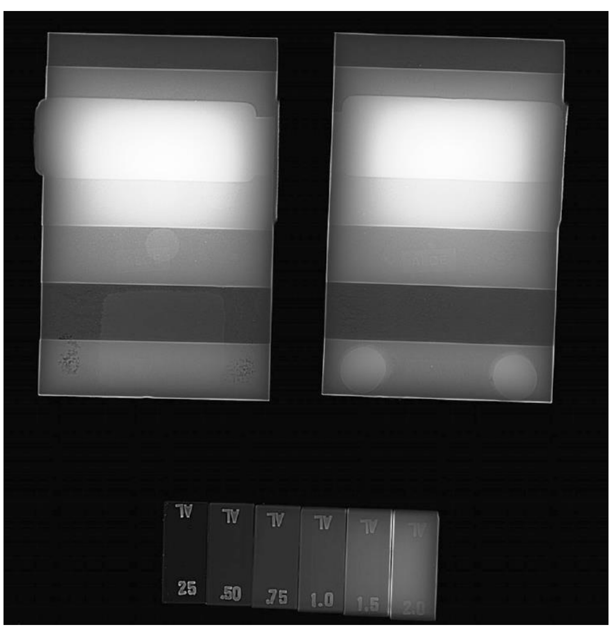

Figure 5: Comparison solubility curves of hydrogen in aluminum alloys.

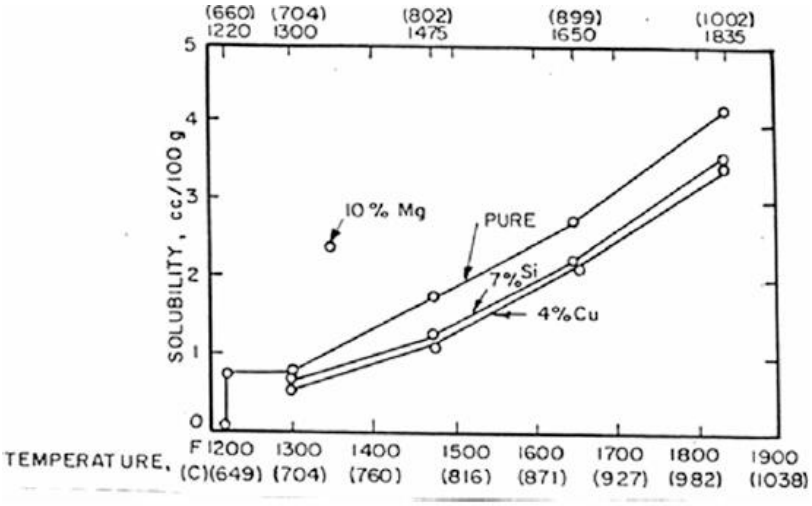

Figure 6: Automotive cylinder head castings produced in Al-8Ce-10Mg alloy.

Figure 7: Rotary engine rotor castings produced in Al-8Ce-10Mg alloy.