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AN ALTERNATIVE EUTECTIC SYSTEM FOR CASTING ALUMINUM ALLOYS I. CASTING ABILITY AND TENSILE PROPERTIES

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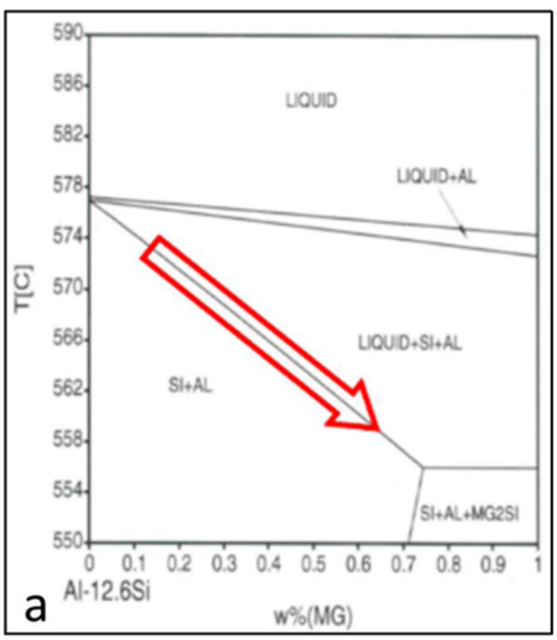
Abstract

Many of the aluminum casting alloys used today are based on the Al-Si eutectic system because it imparts to the alloy excellent feeding ability and resistance to hot tearing. However, strengthening of these alloys by precipitation hardening is limited to a few alloying elements; and therefore, it is desirable to find an alternative eutectic system that would become the basis for a new generation of aluminum casting alloys with higher strength. Towards this end, the Al-Ni, the Al-Fe, and the Al-Fe-Ni eutectic systems are investigated. In this, the first of two papers, the casting ability and tensile properties of these three eutectic compositions are measured and compared to those of the Al-Si eutectic. Based on these comparisons, it is concluded that all three eutectic compositions are viable alternatives to the Al-Si eutectic.

Introduction

The aluminum-silicon system has been made part of many commercial casting alloys in order to improve their castability [1]. However, alloys that are based on this system exhibit limited strength when they are employed at temperatures above 300°C [1-4], and, as shown in Figure 1, the presence of solid solution elements, such as magnesium, copper and zinc in these alloys can further depress the alloy's liquidus temperature. Furthermore, silicon reacts with aluminum and iron - which is invariably present in casting alloys - to form harmful intermetallic compounds such as β-(Al_5SiFe) [5], and it also interacts with some precipitation strengthening elements in unwanted ways [6-8].



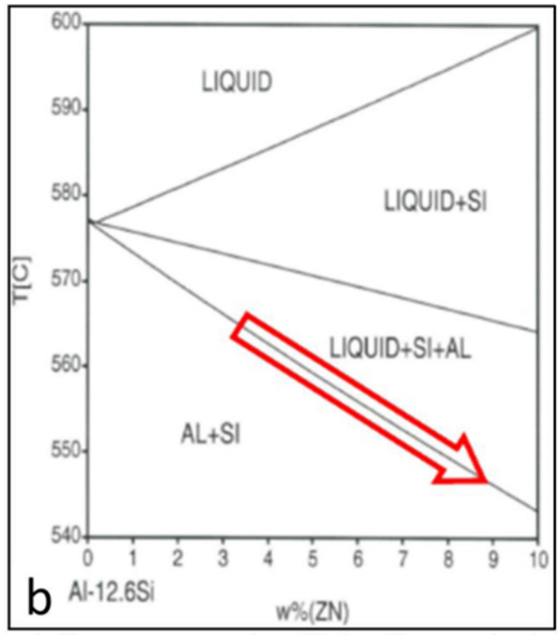


Figure 1. Computer-generated equilibrium diagrams showing the effect of alloying elements on the liquidus of the Al-12.6Si alloy. (a) Effect of magnesium, and (b) effect of zinc.

For these reasons and although aluminum alloys that are based on the Al-Si eutectic system have served the needs of the foundry industry for decades, it is necessary to find new eutectic systems that are castable and can be strengthened by alloying elements to form aluminum-based alloys with superior strength at room and elevated temperature, compared to the traditional alloys that are based on the Al-Si eutectic. Towards this end, this investigation considers the binary Al-Ni and Al-Fe eutectics, as well as the ternary Al-Fe-Ni eutectic as alternatives to the Al-Si eutectic for constituting aluminum casting alloys. The coordinates of these alternative eutectic points are 6.1 wt% Ni - 640°C; 1.8 wt% Fe - 655°C, and (1.85 wt% Fe + 1.25 wt% Ni) - 650°C, respectively [9], and in addition to α-Al, these eutectics contain Al_3Ni at 9.9 vol.%, Al_3Fe at 4.5 vol.% and τ_1-Al_9FeNi at 10.2% vol.%, respectively [9]. The purpose of this investigation is to measure the casting ability (i.e., tendency to hot tear and ability to fill the mold cavity) and the room temperature tensile properties (i.e., ultimate tensile strength, yield strength, elongation and modulus of elasticity) of these eutectic compositions and to compare them to those of the Al-Si eutectic composition as well as to the corresponding characteristics of commercial grade A390 and A206 alloys. Alloy A390 is known for its good fluidity and high resistance to hot tearing and alloy A206 is well recognized for its susceptibility to hot tearing, so they serve as reference points for the investigation.

Materials and Procedure

The eutectic compositions were constituted from pure aluminum ingots (99.99% purity) and Al-15wt% Fe, Al-20wt% Ni and Al-50wt% Si master alloys and were melted in an induction furnace in clean silicon carbide crucibles coated with boron nitride. The melts were degassed with high purity argon gas by means of a rotating impeller degasser for 30 minutes and they were poured at approximately 800°C. The chemical composition of the molten alloys was measured with spark emission spectroscopy taking 6 to 10 measurements for each alloy. The results were averaged and they are shown in Table I.

Table I. Composition of alloys and eutectic systems (wt%).

Alloy	Si	Ni	Fe	Cu	Mg	Zn	Mn	Other	Al
Al-Si	12.60		0.12	0.02	0.07	0.05	0.06		Bal
Al-Si-Sr	12.60		0.12	0.03	0.07	0.05	0.06	0.04Sr	Bal
Al-Ni	0.01	6.10	0.02	0.02					Bal
Al-Fe	<0.03		1.80	<0.01			0.02		Bal
Al-Ni-Fe	<0.02	1.25	1.75	<0.01			0.01		Bal
A390	17.20		0.12	4.45	0.55	<0.10	<0.10	0.15Ti	Bal
A206	<0.05	<0.01	0.04	4.73	0.25	<0.02	0.33	0.22Ti	Bal

An N-Tec Hot Tearing test mold (Figure 2) and an N-Tec Fluidity test mold (Figure 3) were employed in measuring the Hot Tearing Susceptibility (HTS) Index and the Fluidity Index of the Al-Fe, Al-Ni and Al-Fe-Ni eutectics, respectively, as well as those of the modified and un modified Al-Si eutectic and the commercial grade A390 and A206 alloys.

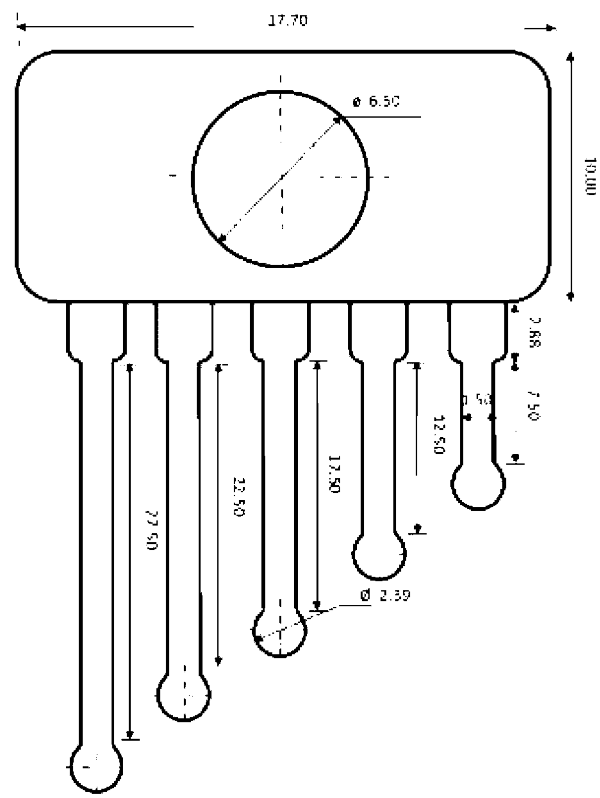


Figure 2. The N-Tec Hot Tearing test mold design (units in mm).

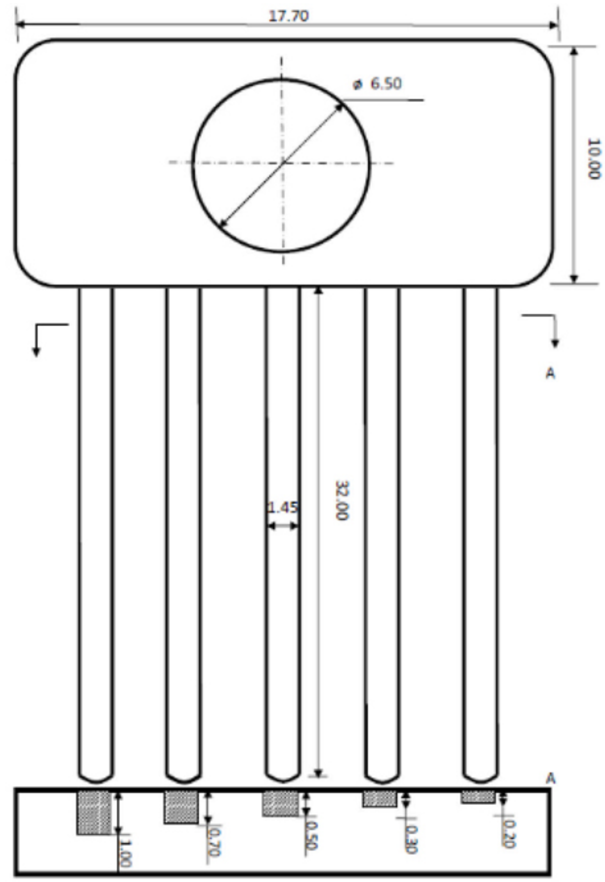


Figure 3. The N-Tec Fluidity test mold design (units in mm).

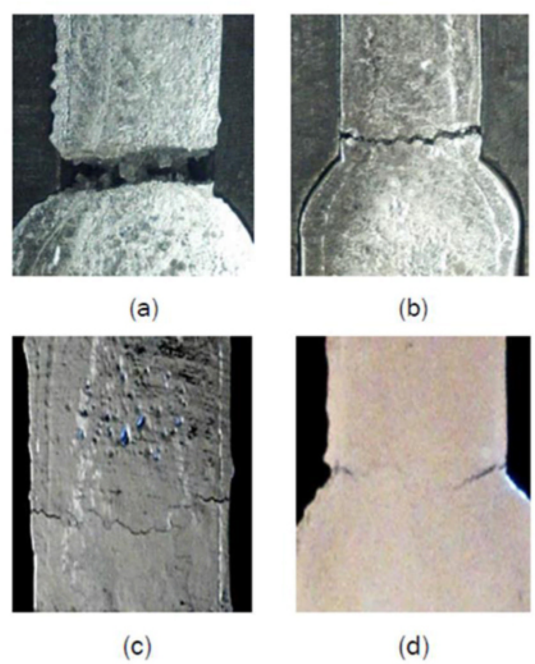


Figure 4. Severities of the crack, (a) complete separation, (b) sever, (c) light and (d) hairline.

The HTS test mold consists of five "dog bone" sections of different lengths that are constrained at one end and have a hot spot along their length. When the alloy is solidified, contraction occurs throughout the bone and cracks appear at the hot spot if the contraction stresses exceed the critical value for the alloy. The Fluidity test mold consists of five straight channels with different thickness. The molds were pre-heated to 250°C before pouring, and at least 5 repetitions were performed for each measurement. The results were averaged and the standard deviations were calculated.

An HTS Index was calculated depending on the visible number of cracks in the dog bones (Figure 4). Cracks usually appear in the longer dog bones due to the increasing constrained shrinkage with increasing length of the dog bone. Thus, both severity and location of the cracks are taken into consideration in the calculation as reflected in Eq. (1)

$$HTS = \sum_i (L_i \times C_i) \quad (1)$$

In Eq. (1), L_i is the length rating of the dog bone where the crack occurred and C_i is the severity rating of the crack. The severity of hot tearing was evaluated from its total crack length and the crack width, as shown in Table II.

Table II. Length rating and crack severity rating used for calculating the HTS Index.

Bar Length Rating		Crack Severity Rating	
Bar Length (cm)	**L_i**	**Hot Tear Type**	**C_i**
27.5	1.00	No Hot Tear	0
22.5	1.22	Hair line	1
17.5	1.57	Light	2
12.5	2.20	Sever	3
7.5	3.67	Complete separation	4

A Fluidity Index (F) was calculated from the summation of the measured distance that the molten metal covers in each channel. With everything else kept constant, molten metal will travel further in a wider channel than in a narrower one. Therefore, both the distance and the length of the channel are taken into consideration in calculating the Fluidity Index as shown in Eq. (2).

$$F = \sum_i (T_i \times L_i) \quad (1)$$

In Eq. (2), F is the overall Fluidity Index of the alloy, T_i is the thickness rating of the channel, and L_i is the length traveled in each channel. The thickness severity rating used for calculating the Fluidity Index is shown in Table III.

Standard round tensile test specimens as described in ASTM standard B557-10 [10] were cast in a cast iron tensile bar mold [11] that was preheated to 427°C. Pouring was performed at approximately 800°C.

The tensile properties measured are the ultimate tensile strength (UTS), the yield strength (YS), the modulus of elasticity (E) and the % elongation (ε%). A Universal Testing machine (Instron, model 5500R) was employed at room temperature at an extension rate of 0.1 in/min. A 2-inch gage length extensometer (MTS model 634.25E-24) was used to measure extension. At least 15 specimens were used for each measurement and the results were averaged and the standard deviations were calculated. Fracture of all specimens took place within the gage length and specimens with severe porosity and/or oxides that would affect the results were excluded. All the numerical results were statistically analyzed and compared by means of one-way ANOVA at a significance level of 5% (α=0.05).

Table III. Thickness severity rating used for calculating the Fluidity Index.

Thickness (cm)	Thickness Rating (T_i)
1.00	1.00
0.70	1.42
0.50	2.00
0.30	3.33
0.20	5.00

Results and Discussion

A. Casting Ability

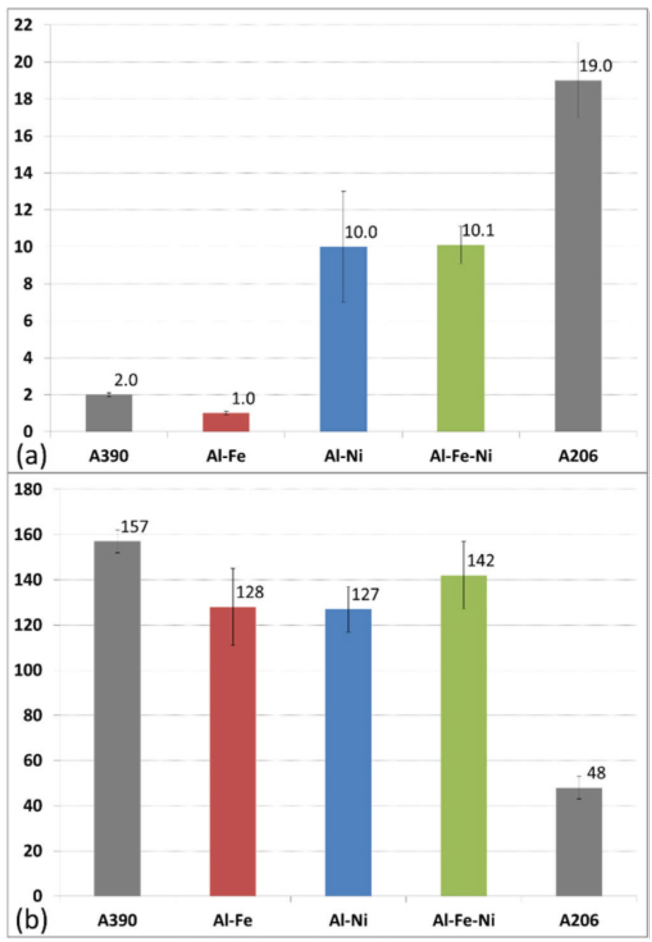


Figure 5. HTS and Fluidity Indices of the three alternative eutectic systems and commercial A390 and A206 alloys.

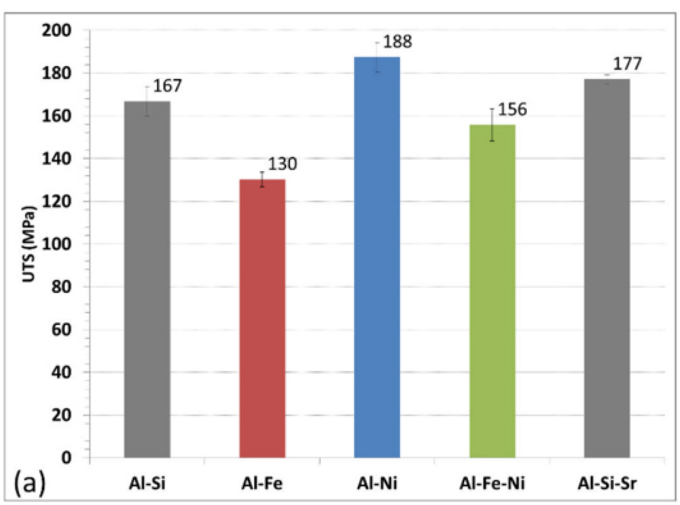
Figure 5(a) shows a comparison of the measured HTS Index of the various alloys. Notice that there is no statistically significant difference between the HTS Index of A390 alloy (HTS = 2.0±0.1) and that of the Al-Fe eutectic (HTS = 1.0±0.1), which suggests that the Al-Fe eutectic has excellent resistance to hot tearing. Also notice that there is no statistically significant difference between the HTS Index of the Al-Ni eutectic (HTS = 10.0±3.0) and that of the Al-Fe-Ni eutectic (HTS = 10.1±1.0), which means that these two systems have similar resistance to hot tearing; and although the HTS Index of the Al-Ni and Al-Fe-Ni eutectics are higher than those of the A390 and the Al-Fe eutectic, they are much lower than that of A206 alloy.

Figure 5(b) shows a comparison of the measured Fluidity Index of the various alloys. The measured Fluidity Index of the A390 alloy is 157±5, which reflects excellent fluidity, and the Fluidity Index of A206 alloy is only 48±5, which reflects limited fluidity. It is clear that the fluidity of all three alternative eutectic systems is superior to that of A206 alloy and closer to that of the A390 alloy.

<u>B. Tensile Properties</u>

The tensile properties of the three alternative eutectic compositions were measured and compared to those of the Sr-modified and unmodified Al-Si eutectic. Figure 6 shows the UTS, YS, E and ε% measured at room temperature.

As shown in Figure 6, the UTS and YS of the Al-Ni eutectic is higher than that of the other eutectics, which is attributed to the presence of coherent Al_3Ni fibers in the structure [12]. The Al-Fe-Ni eutectic has similar UTS and YS to the Sr-modified Al-Si eutectic, while the Al-Fe eutectic has lower UTS and YS. Again, the tensile properties of the Al-Fe-Ni could be attributed to the presence of the eutectic τ_1 phase. The Al-Fe eutectic has lower UTS and YS than the Al-Ni and the Al-Fe-Ni eutectics, but significantly higher elongation - similar to that of the Sr-modified Al-Si eutectic. The elongation of the Al-Ni and Al-Fe-Ni eutectics is similar to that of the unmodified Al-Si eutectic. No statistically significant differences were found between the moduli of elasticity of the eutectic systems, except when comparing $E_{Al\text{-}Si\text{-}Sr}$ with either $E_{Al\text{-}Ni}$ or $E_{Al\text{-}Fe\text{-}Ni}$, in which case $E_{Al\text{-}Si\text{-}Sr}$ is found to be slightly lower than the others.



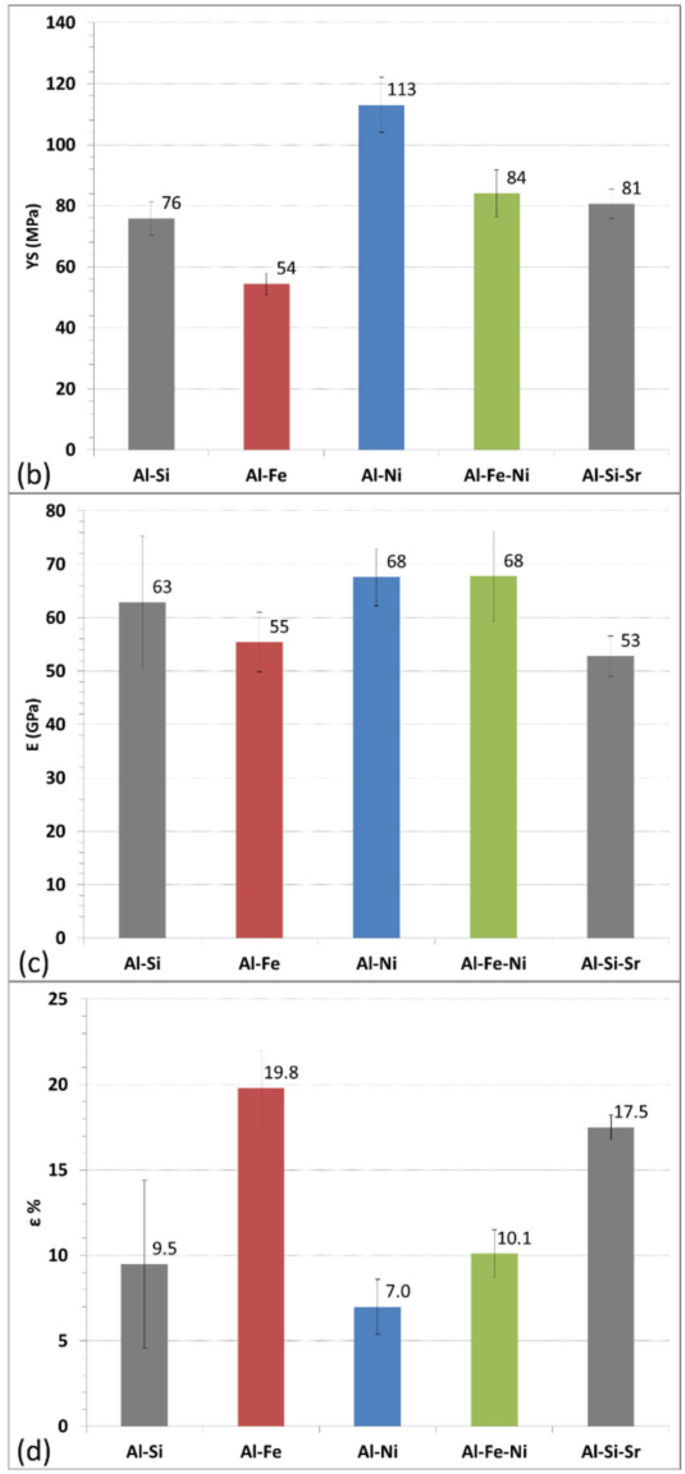


Figure 6. Measured tensile properties of the three alternative eutectic systems compared to those of the un-modified and Sr-modified Al-Si eutectic.

Based on these results, it is submitted that all three alternative eutectic systems present satisfactory strength values that are similar to, or better than, those of the Al-Si eutectic system and comparable to those of the Sr-modified Al-Si system. As the presence of Si in casting alloys has been linked with the formation of harmful intermetallic compounds [5-8], the strength of Al-Si-based alloys may be limited. This limitation may not necessarily apply to the three alternative eutectic systems.

The Al-Ni eutectic has good casting ability with high strength and acceptable elongation, but Ni is significantly more expensive than Si and Fe. On the other hand, the Al-Fe eutectic has excellent casting ability, average strength, and excellent elongation, and is inexpensive compared to the Al-Ni eutectic. Finally, the Al-Fe-Ni eutectic combines characteristics of both the Al-Ni and Al-Fe systems, i.e., good casting ability, good tensile properties, and low cost.

Conclusions

- The casting ability (i.e., susceptibility to hot tearing and fluidity) of the Al-Ni, Al-Fe and Al-Fe-Ni eutectics is superior to that of A206 alloy.
- The room temperature tensile properties of the Al-Ni, Al-Fe and Al-Fe-Ni eutectics are comparable to those of the Al-Si eutectic.

Accordingly, the Al-Ni, Al-Fe and Al-Fe-Ni eutectic systems are viable alternatives to the Al-Si eutectic system for use in aluminum casting alloys.

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