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Impact toughness of Al–Si–Cu–Mg–Fe cast alloys: Effects of minor additives and aging conditions

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ABSTRACT

The effects of Sr modification and aging treatment on the impact toughness of a near eutectic Al–11%Si–2.7%Cu–0.3%Mg–0.45%Fe alloy were investigated. Charpy impact tests were performed on unnotched specimens in the as-cast and heat-treated conditions. It was found that the presence of Fe- and Cu-containing phases increases the alloy brittleness which reduces impact toughness. The eutectic Si phase also plays an important role, where the size/morphology of the Si particles controls the area of α-Al matrix available which affects ductility and toughness. Increasing the Mn content leads to an increase in the volume fraction of the α-$Al_{15}(Mn,Fe)_3Si_2$ phase formed and to sludge formation, which facilitates crack initiation and propagation. Crack propagation occurs mainly via the Al_2Cu and/or α-$Al_{15}(Fe,Mn)_3Si_2$ phases. In the non-modified alloys, the Si phase also plays a considerable role in the fracture process. The impact behaviour of aged alloys is influenced by the amount, size and morphology of hardening precipitates formed in the alloy, depending on the aging conditions. Aging at 240 °C produces a significant increase in the impact energy values of the low Mn-content alloys, as a result of alloy softening. The high Mn-content alloys also show a similar increase in impact energy values, but at a steady level across the same range of aging times, due to the persistence of the α-$Al_{15}(Mn,Fe)_3Si_2$ phase.

1. Introduction

The microstructure exhibited by an alloy plays a vital role in regulating the mechanical properties and, hence, its performance. The main parameters controlling the microstructure of Al–Si casting alloys include composition, melt treatment, solidification conditions, and the heat treatment applied. The principal microstructural constituents of as-cast Al–Si alloys are primary grains of α-Al dendrites, the eutectic silicon phase between the dendrites and secondary eutectic phases such as Mg_2Si or Al_2Cu, as well as ternary phases such as iron-bearing intermetallic compounds [1,2].

This paper reports on the impact properties of a near-eutectic Al–11%Si–2.7%Cu–0.3%Mg–0.45%Fe alloy designed to combine high casting characteristics with improved toughness for use in automotive castings. According to Shivkumar et al. [3], the microstructure is characterized by various parameters such as the grain size, the dendrite arm spacing (DAS), the size, shape and distribution of the eutectic silicon particles, as well as the morphologies and the amounts of intermetallic phases present. Some of these parameters are changed after heat treatment, which consequently affects the resultant mechanical properties [4].

Ye et al. [5] investigated the influence of cooling rate on the dendrite arm spacing of 356 alloy. The authors found that with increase in the cooling rate, considerable decrease in the DAS was observed in the non-modified, sodium-modified, and mischmetal modified alloy. A marked decrease in DAS was observed clearly in the alloy modified by 0.2% mischmetal addition. Ye et al. [5] studied the effect of cooling rate on the microstructure of Al–Si piston alloys (Al–12.2Si–0.85Cu–0.86Fe–0.75Mg). They reported that the different cooling rates have a significant effect on the microstructure of both non-modified and Sr-modified castings. The microstructure of sand cast alloys (i.e., low cooling rate) is less refined than that obtained from chill casting (i.e., high cooling rate), consisting of α-aluminum dendrites, coarse acicular eutectic silicon particles and primary silicon plates.

In view of the alloying elements present (*i.e.*, Si, Cu, Mg and Fe), the effects of Sr and Mn additions and aging conditions were judged as the most relevant metallurgical parameters to investigate in regard to the impact properties of the near-eutectic alloy, due to their influence on the microstructure and its constituents. Briefly, the addition of Sr would modify or change the morphology of the eutectic Si phase from its acicular plate or flake-like form to

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a fibrous form that is beneficial to the mechanical properties; the addition of Mn would "neutralize" the detrimental effects of the platelet-like β-Al$_5$FeSi intermetallic phase by favoring the formation of the more compact and therefore less harmful α-Al$_{15}$(Fe,Mn)$_3$Si$_2$ script phase; while heat treatment would improve the alloy properties of the Cu- and Mg-containing age-hardenable alloy [6].

In the present work, a range of aging temperatures and times were used to cover all possible aging stages/conditions. The influence of individual or combined additions of Mn and Sr was investigated concomitantly with the accompanying aging conditions, to acquire a clear understanding of the impact properties, in order to arrive at a balanced compromise between the impact toughness and strength of the alloy, the latter being measured in terms of the hardness values obtained for the specific alloy/condition.

2. Experimental procedures

The near-eutectic Al–11%Si–Cu–Mg–Fe alloys were prepared using an electrical resistance furnace for melting purposes. The melt temperature was kept at 730 °C ± 5 °C; the molten metal was degassed for ~30 min using pure, dry argon, injected into the melt by means of a rotary degassing impeller. Two levels of Mn, namely 0.45 and 0.65 wt%, and three levels of Sr, 0, 200, and 350 ppm, were added to the alloy melts before pouring. Samples for chemical analysis were taken using standard spectroscopic metallic mold. The molten metal was then cast in an L-shaped permanent steel mold preheated to 450 °C and then cooled in atmospheric air, which provided a cooling rate corresponding to a secondary dendrite arm spacing (SDAS) value of ~45 μm. For each melt composition, a sampling was taken just before pouring for chemical analysis. The chemical analysis was carried out using Spectrolab Jr CCD Spark Analyzer and compositions of the alloys investigated are listed in Table 1. It will be observed from the table that the intended 200 and 350 ppm Sr additions actually correspond to ~165 ppm and ~300 ppm Sr levels. Nevertheless, for the sake of brevity, the Sr levels have been listed as 0, 200 and 350 ppm in all the figures concerned.

Specimens (1 in × 1 in × 3 in) for heat treatment were sectioned from the castings, solution heat treated at 495 °C for 8 h, followed by quenching in warm water (65 °C), and then artificial aging at 155 °C, 180 °C, 200 °C, 220 °C, and 240 °C for times of up to 44 h (an arbitrary aging time) at each aging temperature. Samples for metallographic examination were sectioned from the ends of the as-cast and solution-heat treated bars to monitor the change in the eutectic silicon particle size and shape with heat treatment. The Si particle characteristics were measured using an image analysis system in conjunction with an optical microscope, and are listed in Table 2.

Charpy impact tests were performed on unnotched test bars, which were sectioned and machined from these specimens following ASTM: E23 standards, and investigated in the as-cast and heat-treated conditions. It is worth mentioning here that the use of unnotched impact test specimens for aluminum alloys is recommended in the literature [1,5], since the presence of notches would decrease the absorbed impact energy and thus not provide a correct estimation of the actual impact toughness of the alloy, nor that of the role of the metallurgical parameters studied in controlling the impact behaviour of the alloy, particularly the crack initiation process. An Instron Charpy Impact Testing machine, coupled with a data acquisition system, was used to monitor the impact behaviour of the alloys studied, by measuring the load, total absorbed energy, and total time to fracture. The total absorbed impact energy (E_T) is composed of the crack initiation (E_i) and crack propagation (E_p) energies, where E_i is considered to be the energy at the maximum load, while E_p is calculated as the difference between E_T and E_i. The values reported represent the average of six impact-tested specimens for each alloy/condition along with their standard deviation values (SD less than 5%).

Table 1
Chemical composition of the near-eutectic Al–11%Si–Cu–Mg–Fe alloys used in the present study.

Alloy code	Element (wt%)							
	Si	Cu	Mg	Fe	Mn	Sr	Mn/Fe	Bal.
E1	10.8	2.7	0.38	0.43	0.46	0.0001	1.06	85.2
E2	10.8	2.6	0.38	0.41	0.46	0.0167	1.11	85.3
E3	10.8	2.6	0.38	0.4	0.46	0.0272	1.15	85.3
E4	11.1	2.7	0.37	0.46	0.68	0.0004	1.49	84.4
E5	10.9	2.6	0.38	0.42	0.69	0.0163	1.67	85
E6	11.7	2.7	0.41	0.52	0.63	0.0301	1.23	83.4

E: Base Al–11%Si–Cu–Mg–Fe alloy; (1) 0 ppm Sr; (2) 200 ppm Sr; and (3) 350 ppm Sr.

Table 2
Eutectic silicon particle characteristics of alloys studied (as-cast and solution heat-treated conditions).

Alloy	Condition	Si particle characteristics		
		Areal density (#/mm^2)	Area (μm^2)	Length (μm)
E1	As-cast	2300	36.8 ± 61.7	12.7 ± 16.1
	SHT	1386	57.4 ± 76.5	16.8 ± 17.8
E2	As-cast	20,616	5.3 ± 10.1	4.2 ± 5.1
	SHT	26,362	5.6 ± 8.6	3.4 ± 3.5
E3	As-cast	26,826	4.8 ± 9.3	3.8 ± 4.7
	SHT	26,835	5.0 ± 8.1	3.4 ± 3.5
E4	As-cast	2298	38.9 ± 59.6	13.7 ± 16.6
	SHT	1342	59.2 ± 73.5	18.1 ± 19.0
E5	As-cast	14,574	7.2 ± 12.0	5.2 ± 5.8
	SHT	36,840	3.6 ± 5.8	2.7 ± 2.6
E6	As-cast	22,893	4.7 ± 9.1	3.7 ± 4.7
	SHT	17,429	7.1 ± 10.1	4.5 ± 4.1

SHT: Solution heat treated condition.

Hardness measurements were also carried out on the two-halves of each impact-tested sample (four measurements were taken from two perpendicular surfaces in each case) using a Brinell hardness tester (employing a 10 mm steel ball and a load of 500 kg-force applied for 30 s). The average hardness values of the eight readings and their corresponding standard deviations values

Table 3
Brinell hardness values of alloys studied after aging for 4 h, 16 h, and 44 h at 155 °C, 180 °C, and 240 °C aging temperatures.

Alloy	Aging time (h)	Hardness (BHN)		
		155 °C	180 °C	240 °C
E1	4	116.0 ± 2.5	133.0 ± 3.7	103.5 ± 2.3
	16	138.6 ± 6.1	131.5 ± 1.5	94.8 ± 0.8
	44	144.9 ± 1.8	125.9 ± 2.3	86.4 ± 0.4
E2	4	109.1 ± 1.0	118.9 ± 1.1	95.8 ± 2.0
	16	129.6 ± 2.6	122.8 ± 3.1	89.3 ± 1.8
	44	132.0 ± 1.9	118.9 ± 2.1	78.8 ± 1.4
E3	4	108.4 ± 2.1	126.7 ± 3.6	99.5 ± 0.9
	16	128.1 ± 2.3	122.7 ± 2.4	86.7 ± 0.9
	44	130.0 ± 2.2	115.6 ± 2.0	79.6 ± 0.4
E4	4	116.0 ± 4.2	136.5 ± 2.3	109.3 ± 0.7
	16	140.4 ± 3.2	137.3 ± 2.5	94.1 ± 2.3
	44	145.8 ± 1.8	127.0 ± 3.4	87.2 ± 1.2
E5	4	117.4 ± 0.9	123.1 ± 2.7	101.2 ± 1.0
	16	133.2 ± 3.0	126.8 ± 3.4	91.0 ± 1.7
	44	131.8 ± 1.1	115.1 ± 2.2	79.3 ± 1.0
E6	4	112.9 ± 3.1	124.5 ± 3.0	100.2 ± 0.9
	16	122.9 ± 3.3	122.6 ± 2.7	86.4 ± 0.7
	44	129.7 ± 3.4	118.5 ± 1.9	80.4 ± 1.8