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The ambient and high temperature deformation behavior of Al–Si–Cu–Mg alloy with minor Ti, Zr, Ni additions

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ABSTRACT

The principal aim of the present work was to investigate the effects of minor additions of nickel and zirconium on the strength of cast aluminum alloy 354 at ambient and high temperatures. Tensile properties of the as-cast and heat-treated alloys were determined at room temperature and at high temperatures (190 °C, 250 °C, 350 °C). The results show that Zr reacts only with Ti, Si and Al. From the quality index charts constructed for these alloys, the quality index attains minimum and maximum values of 259 MPa and 459 MPa, in the as-cast and solution-treated conditions; also, maximum and minimum values of yield strength are observed at 345 MPa and 80 MPa, respectively, within the series of aging treatments applied. A decrease in tensile properties of ∼10% with the addition of 0.4 wt.% nickel is attributed to a nickel–copper reaction. The reduction in mechanical properties due to addition of different elements is attributed principally to the increase in the percentage of intermetallic phase particles formed during solidification; such particles act as stress concentrators, decreasing the alloy ductility. Tensile test results at ambient temperatures show a slight increase (∼10%) in alloys with Zr and Zr/Ni additions, particularly at aging temperatures above 240 °C. Additions of Zr and Zr + Ni increase the high temperature tensile properties, in particular for the alloy containing 0.2 wt.% Zr + 0.2 wt.% Ni, which exhibits an increase of more than 30% in the tensile properties at 300 °C compared with the base 354 alloy.

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1. Introduction

In Al–Si casting alloys, applications are generally to be carried out at temperatures of no more than 230 °C [1]. This recommendation is made in view of the fact that, for certain applications such as those required by the automotive industry, these alloys must operate over a wide range of temperatures and stress conditions where temperatures are liable to rise even higher than 230 °C. Alloying elements such as copper and magnesium are often added to improve alloy strength at room temperature as well as at higher temperatures. When they are affected by temperatures above 190 °C, the major alloy strengthening phases which include the θ'(Al_2Cu) and S'(Al_2CuMg) phases will tend to become unstable, coarsen rapidly, and then dissolve, leading to the production of an alloy which has an undesirable microstructure for high temperature applications. Apart from these phases, when a casting is produced, there are other microstructural features that contribute to strength, ductility and durability; these include secondary dendrite arm spacing, grain size, and interdendritic Si particles [2,3].

Minor additions are often made to high strength wrought aluminum alloys for the purpose of regulating grain structure and inhibiting recrystallization during heat treatment, which occurs as a result of the obstructive action of coherent particles with dislocations [4]. According to the literature [5], it would be necessary to obtain a microstructure containing thermally stable and coarsening-resistant dispersoids in order to improve mechanical properties at high temperatures in an aluminum alloy. These dispersoids or particles will be resistant to coarsening if the energy of their interface with the matrix is low, and if the diffusivity and solubility of the rate-controlling element are both minimal. Of all the transition metals, zirconium has the smallest diffusion flux in aluminum [6], and its addition to aluminum base alloys results in the formation of the Al_3Zr phase, which precipitates out during the initial solution heat treatment in the form of metastable $L1_2$ Al_3Zr particles. These particles are resistant to dissolution and coarsening; they can also control the evolution of the grain and subgrain structure, thereby making it possible to increase strength and ductility in the precipitation-hardened T6 condition [2] or

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during subsequent processing operations, such as the hot rolling of wrought alloys. The addition of small amounts of Zr to wrought aluminum alloys has been widely studied, although the effects of Zr on cast aluminum alloys is a topic which has been infrequently discussed in the literature to date [6,7].

In a number of studies on Al–Si casting alloys, it was shown that Ni contents of less than 2% do not affect the mechanical properties, whereas nickel variations of up to 2–3% affect only the specific gravity from among the usual physical properties. Nickel is present largely as a relatively massive acicular dispersion of Al_3Ni and the amount of this compound has been shown to increase with increasing Ni content. Effective strengthening would thus necessitate a much finer dispersion of Al_3Ni or a much higher volume fraction of the coarse compound, leading to the view that much larger amounts of nickel would be necessary for any useful improvement in strength. With regard to aluminum casting alloys, a high percentage of Ni seems not to be practical, mainly because it would increase the cost of the alloy [6].

The principal aim of the present research work is to investigate the effects of minor additions of Ni and Zr, on the strength of the cast aluminum alloy 354 at high temperatures. In order to meet this principal goal it is necessary to attain the following objectives:

(1) To determine the tensile properties of the alloys studied at room temperature, using different aging conditions of temperature and time.
(2) To obtain the high temperature tensile properties at different temperatures for selected alloys/conditions based on the room temperature tensile test results.

2. Experimental procedure

Alloy 354 modified with 200 ppm of strontium and grain refined using 0.25 wt.% Ti (Al–5%Ti–1%B) will be used as the base alloy (Alloy A). The chemical composition in wt.% of the as-received 354 alloy is listed in Table 1a. The addition of zirconium and nickel will be carried out using Al–20 wt.% Zr and Al–20 wt.% Ni master alloys, respectively. Table 1b shows the actual compositions and codes of the alloys used in the present study.

The material used to obtain the present alloys was melted in a 120-kg capacity SiC crucible, using an electrical resistance furnace. The metal temperature was maintained at 780 °C, while the melt was degassed using pure, dry argon injected into the melt for 20 min by means of a rotating graphite impeller at 200 rpm, as shown in Fig. 3.10. Grain refining and modification of the melt were carried out using Al–5% Ti–1% B and Al–10% Sr master alloys, respectively, to obtain levels of 0.25% Ti and 200 ppm Sr in the melt. Master alloys were added only instants before degassing to ensure homogeneous mixing of the additives together with the degassing. The melt was poured into a preheated ASTM: B-108 permanent mold (preheated to 460 °C). Heat treatment of the test bars used for tensile testing involves solution heat treating them at 495 °C for 8 h, followed by quenching in warm water at 60 °C, after which artificial aging is applied according to the regime listed in Table 2.

For the high temperature tensile tests, samples from selected conditions were tested to the point of fracture using an Instron Universal mechanical testing machine at a strain rate of 4×10^{-4} s^{-1}. The heating furnace installed on the testing machine is an electrical resistance air forced box type having the dimensions 30 cm × 43 cm × 30 cm. The extensometer, which is cooled by circulated water, was used in the tests to measure the extent of deformation in the samples. The yield strength (YS) was calculated according to the standard 0.2% offset strain, and the fracture elongation was calculated as the percent elongation (%E1) over the 25.4 mm gauge length as recorded by the extensometer. The ultimate tensile strength (UTS) was obtained from the data acquisition system of the universal machine. In order to reach and stabilize the intended test temperature during the tests, at the time that the samples were mounted in the tensile machine, the furnace was already pre-set at the required temperature; also, these samples were kept mounted in the furnace of the tensile testing machine for 30 min to reach the required temperature, then soaked at this temperature for 1 h before the start of the test.

For the purposes of determining the reactions taking place during solidification, the molten metal was poured into an 800 g capacity graphite mold preheated to 650 °C so as to obtain close-to-equilibrium solidification conditions at a cooling rate of 0.35 °C s^{-1}. Thermal analysis was carried out using a chromel/alumel Type K thermocouple inserted into the crucible through a

Table 1a
Chemical composition of the as-received 354 alloy.

Element (wt%)					
Si	Fe	Cu	Mn	Mg	Al
9.1	0.12	1.8	0.0085	0.6	87.6

Table 1b
Chemical composition of the alloys used in this work (wt%).

Alloy/element	Si	Fe	Cu	Mn	Mg	Ti	Sr	Ni	Zr	Al
A	9.43	0.08	1.85	0.01	0.49	0.22	0.0150	–	–	87.5
D	9.16	0.08	1.84	0.01	0.49	0.22	0.0149	0.46	–	87.7
E	9.10	0.07	1.83	0.00	0.45	0.21	0.0145	–	0.39	87.7
F	9.10	0.08	1.86	0.00	0.46	0.22	0.0122	0.40	0.39	87.5
G	9.01	0.08	1.85	0.00	0.45	0.21	0.0127	0.21	0.190	87.8

Table 2
Artificial aging conditions used for room temperature tension tests.

Temperature (°C)	Aging time (h) and aging condition codes											
	2	4	6	8	10	12	16	20	24	36	48	72	100
155	1	2	3	4	5	6	7	8	9	10	11	12	13
170	14	15	16	17	18	19	20	21	22	23	24	25	26
190	27	28	29	30	31	32	33	34	35	36	37	38	39
240	40	41	42	43	44	45	46	47	48	49	50	51	52
300	53	54	55	56	57	58	59	60	61	62	63	64	65
350	66	67	68	69	70	71	72	73	74	75	76	77	78

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