Investigation of fracture behaviour of high-strength aluminium alloys in the as-cast condition

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1. Introduction

Vertical direct-chill (DC) casting process has been the mainstream of aluminium industry for the production of billets and ingots since the late 1930s largely due to its robust nature and relative simplicity [1]. Unfortunately the process can produce distortions in the ingot, and cracks can form owing to the non-uniform, high-rate heat removal due to the direct contact of a bottom block and cooling water with the partially solidified ingot. Further increase of thermal stresses in the solid state accompanied by weaker mechanical properties of the alloy in certain temperature ranges may lead to crack propagation and catastrophic failure [2]. Variation of mechanical properties in different ingot sections which is the result of high temperature gradients in the billet upon solidification can also cause different susceptibility of the material to cracking [3, 4]

In contrast to pre-solidification cracks (hot cracks), which form at temperatures above the solidus, post-solidification cracks (cold cracks) propagate in a fully solid material [5]. Cold cracks can damage the entire ingot by splitting it open, which results in complete scrapping of the ingot.

Cold cracking is characteristic of alloys which are brittle in the as-cast conditions. These alloys (mainly high-strength Al-alloys) are apparently unable of withstanding high stresses generated during DC casting.

In order to study cold cracking phenomenon in more detail, sufficient information on mechanical properties of such alloys in the as-cast condition (without stress relieving and homogenization) is required. The data on these properties are, however, seldom available in literature. The alloys in question are wrought alloys and most of the tests are performed on wrought products after deformation and heat treatment. Scattered information is available on the properties of ingots, but then only after homogenizing or stress-relief anneals [4,6]. This lack of experimental data on the mechanical properties of as-cast high-strength wrought alloys, especially in a range of temperatures and strain rates relevant to DC casting, makes thermo-mechanical simulations of cold cracking unreliable. This paper is a first step in bridging this gap. The results are reported on mechanical properties of as-cast 7XXX-series alloys in a wide range of subsolidus temperatures. The structure and fractures are examined in an attempt to interpret the results of mechanical testing.

2. Experimental procedure

Three groups of samples used in this research work are as follows (see Table1):

1- AA7050 cast in a copper mould with 6 cylindrical cavities 20 mm in diameter and 320 mm in length at a melt temperature of 720 °C. Four groups of samples were prepared as listed in Table 1. Aluminium of different initial purity was taken as a starting material (LP – 99.7% Al; HP – 99.95% Al), further Al–47.7% Cu, Al–25.1% Mg, Al–5.8% Zr master alloys, and pure Zn were used for preparing the alloys. As one can see from Table 1, the concentrations of impurities, i.e. Fe and Si, in LP and HP alloys are very close to each other. The alloys were cast in the said mould that was either preheated (HM) or cooled (CM), or kept at a room temperature (GR, NG). One alloy modification was grain refined (GR) with an Al–3% Ti–1% B master alloy.

2- AA7050 billet produced by DC casting with degassing of the molten metal and supplied by Corus-Netherlands (IJmuiden) (7050 (DC cast) in Table 1).

3- AA7475 DC cast billet produced by a third party and cold-cracked at the sawing attempt (7475 in Table 1).

Charpy impact toughness tests were conducted on 7050 samples cast in the copper mould and 7475 samples over a temperature range from room temperature to 500 ºC (at 100 ºC steps). ASTM-E23 notched samples were first heated up to desired temperatures in a small chamber oven for 5 minutes and then immediately transported to the machine for tests. Tensile mechanical properties of 7050 samples cast in the copper mould were measured using a Gleeble-1500 thermomechanical simulator. The samples were heated through the Joule effect (from room temperature to 400 ºC at 100 ºC steps) at a rate of 10 K/s, kept for 10 seconds and then uniaxially deformed at three strain rates of 10^{-2}, 10^{-3} and 10^{-4} s^{-1}. The range of strain rates was chosen to resemble those typical of DC casting [7]. A K-type (Chromel–Alumel) thermocouple was used to monitor the temperature in the middle of the gauge length, while the changes in diameter were monitored simultaneously using an extensometer.

Table1. Chemical composition of tested alloys

Alloy *	Alloying elements, wt %								
	Zn	Mg	Cu	Zr	Cr	Mn	Ti	Fe	Si
7050-HP-NG	6.1	2.0	2.5	0.09	<0.01	<0.01	<0.01	0.19	0.06
7050-HP-GR	6.1	2.0	2.6	0.09	<0.01	<0.01	0.03	0.20	0.07
7050-LP-HM	6.0	1.9	2.4	0.1	<0.01	<0.01	<0.01	0.16	0.04
7050-LP-CM	6.0	2.0	2.4	0.1	<0.01	<0.01	<0.01	0.16	0.04
7050 (DC cast)	6.3	2.4	2.5	0.1	<0.01	0.04	0.03	0.07	0.04
7475	5.45	2.5	1.75	–	0.20	0.025	0.057	0.09	0.06

* HP-NG: non-grain refined; HP-GR: grain refined; LP-HM: cast in hot mould; LP-CM: cast in cold mould.

Grain size and dendrite arm spacing were measured based on ASTM-E112 using polarized light in an optical microscope Neophot 30. A scanning electron microscope Jeol JSM-6500F (SEM) and the optical microscope (OM) were used for fractographic observations. To study the effect of porosity on mechanical properties, specific gravity measurements were performed based on Archimedes' principle. Having used the 7050 (DC cast) alloy as a reference sample (presumed dense as a result of degassing), the porosity percentage was then calculated.

3. Results

3.1. Mechanical tests

Figure 1 shows the changes in the absorbed energy during the Charpy impact toughness test for 7050 (HP-NG and HP-GR) and 7475 alloys in the as-cast condition. As can be seen from the figure, there is little increase in the amount of absorbed energy until 200 °C, hence the material is quite brittle. Then the absorbed energy increases, reaches maximum at 400 ºC and afterwards falls at 500 ºC. It is obvious from these results that there are two temperature ranges where material behaves more brittle, i.e. at temperatures close to room temperature and above the non-equilibrium solidus (465–469 ºC [8]). The 7475 DC-cast alloy appears to absorb more energy before failure at 400 ºC than 7050 alloys cast in the copper mould. Below 400 ºC, there is not much difference in the behaviour of 7050 samples, whereas at 500 ºC the grain refined alloy (7050-HP-GR) has an advantage. The behaviour of 7050-LP-HM and 7050-LP-CM is similar to that of 7050 alloys shown in Fig. 1, and falls in the same range of values.

Figure 2 shows the effect of temperature on ductility (% reduction in area) of 7050 samples cast in the copper mould, respectively. Apparently the material becomes quite brittle at temperatures below 200 ºC. The yield strength increased as the temperature decreased (in agreement with the results of Miklyaev [9]) in either linear manner or passed through a maximum at 100 ºC. It can also be derived that structure differences induced by composition or solidification conditions become more important for strength and high-temperature ductility at lower temperatures, where the difference in the results between different alloys arises. It can be also concluded that the alloys cast in cold mould (LP-CM) or grain refined (HP-GR) possess better mechanical features than other tested alloys from this group. Further study of the stress-strain curves revealed that at high temperatures (300 and 400 ºC) the yield strength increases as the deformation rate increases, but at lower temperatures (beginning at 200 ºC) the material behaviour becomes either strain-rate independent, or with increasing the strain rate the material fails at lower stresses, before reaching its yield point.

3.2. Structure examination

EDS analysis revealed that under non-equilibrium casting conditions up to 2 wt% Mg, 1.2 wt% Cu and 3 wt% Zn and 0.03 wt% Fe can be dissolved in the matrix. Relatively high solidification rates present under practical casting conditions results in the formation of non-equilibrium eutectics. Microcracks can be observed inside some of such intermetallic particles as well as at the matrix–eutectic interface (Fig. 3c).

Quantitative metallographic results are shown in Table. 2. As can be seen the samples cast in the hot mould have the largest grain size. Dendrite arm spacing does not vary much between different samples. Porosity and density values for all 7050 alloys cast in the copper mould are also listed in Table 2 (with the 7050 (DC cast) alloy taken as a reference). The non-grain refined samples have the lowest density and consequently the highest amount of porosity. On the contrary, the grain refined samples show the highest density although the scattering in the results is high. Samples cast in the cold mould appear to have less porosity and the deviation from the mean value is also smaller.

Table 2. Structure parameters of the tested alloys.

Alloy *	Grain size, μm	Dendrite arm spacing, μm	Density, g/cm^3	Porosity, %
7050-HP-NG	160±8	15±0.4	2.80±0.02	3.6±0.5
7050-HP-GR	40±5	19±0.7	2.85±0.05	3.2±0.9
7050-LP-HM	240±9	18±0.5	2.80±0.02	3.3±0.5
7050-LP-CM	170±9	17±0.5	2.85±0.01	2.4±0.5
7050 (DC cast)	–	–	2.90±0.03	–
7475	171±7	20±1	–	–

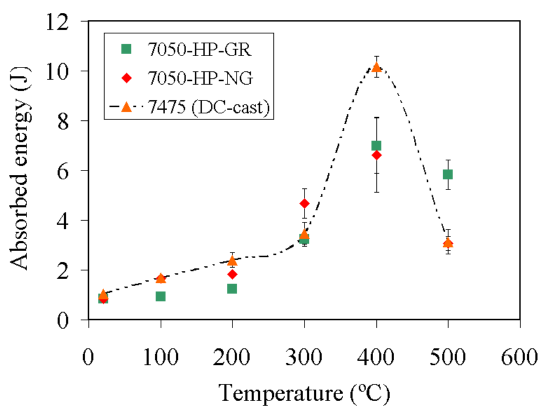

Figure 1. Charpy impact toughness for two 7050 alloys cast in the copper mould (GR: grain refined; NG: non-grain refined) and DC cast 7475 samples.

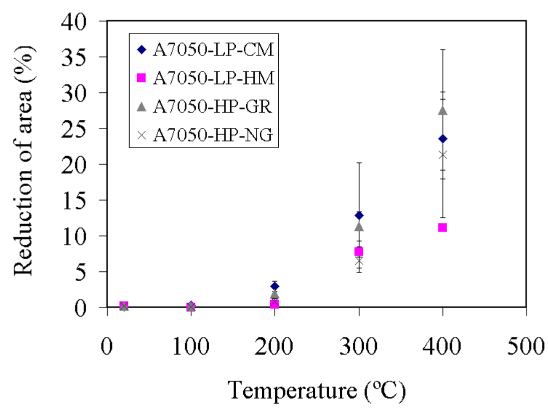

Figure 2. Average reduction in area of 7050 samples cast in the copper mould (see Table 1) tested at different temperatures at a strain rate of 10^{-2} s^{-1}.

4. Discussion

Examination of fracture surfaces can help in understanding the results on mechanical properties (Figs. 1, 2). The dimples on the fracture surface of a 7475 sample failed at 400 ºC were evidence for the highest energy absorption due to plastic deformation at this temperature. At the same time, cracked intermetallic particles were observed inside the dimples, revealing the weak link of the structure. At 500 ºC, which is above the non-equilibrium solidus temperature (465–469 ºC [8]) of this alloy, the sample failed intergranularly and the magnitude of absorbed energy is smaller as a result of liquid metal embitterment of the grain boundaries. Eutectic patches and secondary intergranular cracks are typical of this fracture (Fig. 3a). From room temperature to 200 ºC the fracture mode is quite brittle and no sign of plastic deformation is observed. Failure also occurs intergranularly with the evidence of fractured or cleaved eutectic particles on fracture surfaces (Fig. 3b). This is the temperature range where the cold cracking is likely to occur. Intergranular fracture mode with secondary cracks, pores and cleaved eutectic patches is characteristic of low-temperature mechanical behaviour of tested alloys. Another way of triggering brittle fracture can be decohesion of constitutive particles from the matrix or fracture of particles proper (Fig. 3c). Main reason for decohesion and cracking is the difference of thermal expansion coefficients (TEC) of intermetallic particles (low TEC) and aluminium matrix (high TEC), and thermal stresses generated at the particle–matrix interface as a result of thermal contraction during cooling. The fracture occurring in this way can be classified as cold cracking.

Porosity, which can be either the result of reduced solubility of H_2 in the metal at lower temperatures or shrinkage during solidification, results in scattering of mechanical properties and may cause fracture of the material before it reaches the yield point (especially at low temperatures). Reduced porosity in samples solidified in the cold mould can be a result of hydrogen quenching into the solid solution during solidification.

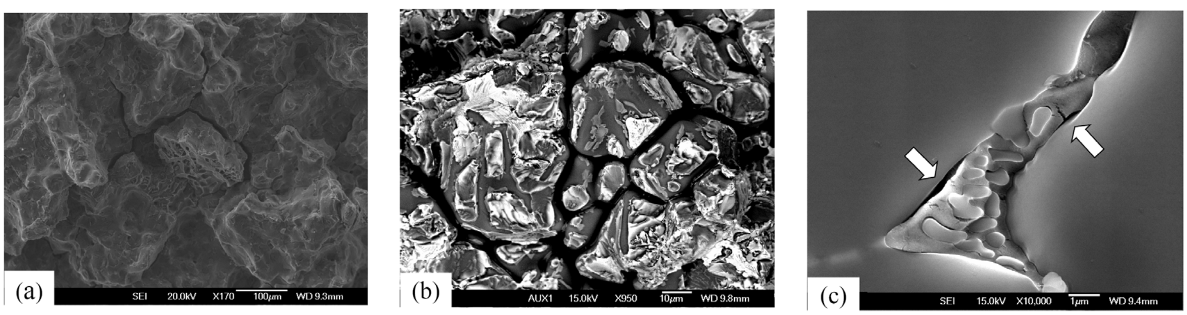

Figure 3. (a) Fracture surface in a 7475 alloy failed during Charpy test at 500ºC, fracture is intergranular with secondary cracks, SEM; (b) electron-backscattered image of the fracture surface of a 7050-HP-NG sample failed during Charpy test at room temperature, non-equilibrium eutectics and intermetallics appear brighter, signs of cleavage are visible in some of these particles; and (c) SEM image showing micro-cracks at the interface of the α-aluminium matrix and non-equilibrium eutectics, and inside a eutectic constituent in a 7050-LP-CM sample;

5. Conclusions

Charpy impact toughness and tensile tests at room and elevated temperatures were performed on samples of 7050 alloy cast in the copper mould with the aim to investigate the influence of the strain rate and temperature on the mechanical properties. Impact toughness tests were also performed on samples from a DC-cast 7475 billet. Within the entire tested temperature range, all tested alloys appear to be essentially brittle, especially below 200 °C. The material shows some ductility at 400 °C and at low strain rates at temperatures as low as 300°C. The lower the temperature, the more brittle is the material, the less strain-rate dependent are the mechanical properties, and the higher is the probability of the failure before reaching the yield point. In addition, both strength and ductility decreased sharply at temperatures above the non-equilibrium solidus. Investigation of the fracture surfaces revealed that the material fails in intergranular manner, with non-equilibrium eutectics acting as liquid or brittle, solid bridges between dendrite arms. Porosity and micro-cracks (especially at the matrix-secondary phase interface) are the apparent microstructural features that may trigger the fracture and provide easy way for crack propagation. Porosity is also a factor causing scattering in the results.

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