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HORIZONTAL SINGLE BELT STRIP CASTING (HSBC) OF Al-Mg-Sc-Zr ALLOYS

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Abstract

Scandium containing Al-Mg alloys exhibit significant potential for use in aerospace applications, such as air frames and stiffened panels. Zirconium additions further improve the room temperature (RT) workability, elevated temperature resistance and mechanical properties of these alloys. In this study, the capability of the Horizontal Single Belt Strip Casting (HSBC) technology for casting and processing of Al-Mg-Sc-Zr alloys was investigated. The alloys were strip cast on the horizontal single belt strip caster located in McGill's Metals Processing Centre (MMPC). Detailed micro-structural characterization of strip-cast Al-Mg-Sc-Zr alloys was conducted via Optical Microscopy (OM), Scanning Electron Microscopy (SEM), and Electron Backscatter Diffraction (EBSD). Additionally, the surface quality of strips was evaluated via 3D profilometry measurements and analyses. Finally, mechanical properties of the cast strip products were evaluated and compared with equivalent cast alloy structures associated with the slower cooling rates specific to direct chill (DC) casting.

Introduction

Medium strength, magnesium containing, aluminum alloys exhibit high ductility, as well as good corrosion resistance and good weldability. Combined additions of Sc and Zr to the Al-Mg system results in the development of high-strength Al alloys with improved workability and high temperature resistance [1-4]. Al-Mg-Sc-Zr based alloys have become important candidates for western aerospace applications [5].

In the Al-Mg-Sc-Zr system, Mg is mainly present in the dissolved state, generating solution strengthening, whereas Sc and Zr additions provide strengthening through the formation of $Al_3(Sc,Zr)$ precipitates, and by grain refinement. The high mechanical strength of this system results mostly from Orowan Strengthening via dislocation pinning [1-6]. In addition to this, it is reported that $Al_3(Sc,Zr)$ precipitates also delay recrystallization during hot working, which allows alloys based on the Al-Mg-Sc-Zr system to maintain their strength at higher temperatures versus equivalent alloys without Sc/Zr [6]. Gravity casting has been used as the processing route, followed by heat treatment, in most of the studies, since the main focus was precipitation hardening. However, Kendig et al. reported that the influence of grain boundary strengthening on Al-6Mg-2Sc-1Zr (wt.%) alloy's mechanical strength was higher than both the effects of precipitation and solution strengthening [7].

Horizontal Single Belt Strip Casting (HSBC) is an advanced continuous casting process in which high cooling rates can be achieved. Evolution in heat transfer and solidification for non-ferrous alloys has been extensively investigated by the research group of the MMPC [8]. Similarly, the research group at Clausthal University has studied the solidification of Mg alloys. High solidification rates not only reduce as-cast grain sizes, but also eliminate anisotropy and segregation effects.

The objective in this study was to investigate the suitability of HSBC technology in the casting and processing of high strength Al-Mg-Sc-Zr alloys.

Experimental Procedure

Pure Al, pure Mg and master alloys of Al-2Sc (wt%) and Al-10Zr (wt.%) were used to cast Al-Mg-Sc-Zr alloys, aiming at a target composition of Al-4Mg-0.6Sc-0.12Zr (wt.%). The aluminum melt (~130 kg) was prepared in an induction furnace. The furnace then was moved to the casting station where the melt was displaced into the launder of a low head metal delivery system. Then, the liquid was metered through a slot nozzle, allowing the molten alloy to flow onto the moving, water-cooled, graphite coated, endless steel belt, 2.6 m long. Continuous, thin sheets of Al-Mg-Sc-Zr alloys were formed *(thickness: ~5-7 mm, width: 7-10 cm)*. The chemical compositions of the 3 different casts are given in Table 1.

Table I. Chemical Compositions of Cast Alloys (ICP Analysis)

Samples	*Mg*	*Sc*	*Zr*	*Al*
1	3.788	0.460	0.083	*Bal.*
2	3.877	0.368	0.038	*Bal.*
3	4.112	0.337	0.023	*Bal.*

An example of the temperature variation during casting is shown in Figure 1. A thermocouple was placed near to the slot nozzle in the delivery launder for measuring melt temperature.

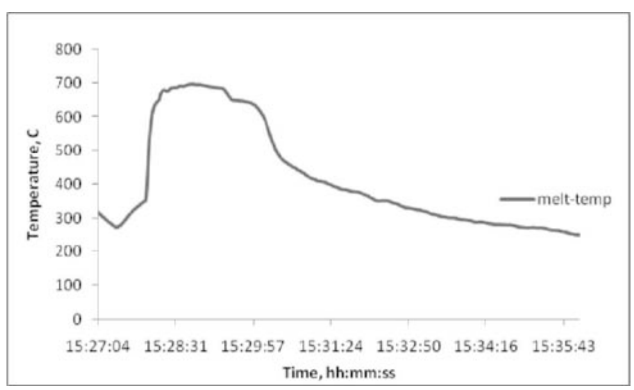

Figure 1. Temperature variation during HSBC process

Once the pre-heater cover over the launder was removed, the temperature of the exposed thermocouple's tip decreased as it became exposed to cold air; then the melt level in the launder increased, and submerged the thermocouple, after which a constant temperature of 694~695°C was achieved during the casting operation. Once the cast was completed, the melt level in the launder lowered, causing the thermocouple temperature readings to slowly decrease.

Specimens for optical and scanning electron microscopy (SEM) were prepared by grinding and polishing, down to a 1µm diamond paste in an alcohol-based lubricating fluid. An etchant made up of Kellers solution (5 ml nitric acid, 3 ml hydrochloric acid, 2 ml hydroflouric acid and 190 ml distilled water) was used for optical microscopy analysis. For EBSD analysis, samples were additionally polished down to 0.04µm, using a vibratory polisher for up to 6 hours. SEM analysis was conducted using a Hitachi S-3000N VP-SEM and a Philips XL-30 Field Emission-STEM (FE-STEM) at 20kV. EBSD data was collected and analyzed using TSL software with 0.5µm intervals. Additionally, surface roughness profiles of Al-Mg-Sc-Zr strip casts were measured using a NANOVEA 3D profilometer, while Vickers hardness (HV) values were measured using a 5 kg load.

Results

Thermodynamic Calculations

The assessment of some of the equilibrium phases that would form in the strip-cast structure was made through thermodynamic calculations using FactSage software. The isopleths drawn for a constant Zr level of 0.02 wt.% and varying Sc levels (0-2 wt.%), indicated that within the analyzed composition ranges for the strip-cast alloys (Table I), both Al_3Sc and Al_3Zr phases should form from the liquid aluminum alloy, as primary phases (Figure 2). Additionally, the β-AlMg phase forms from the α-Al matrix, during the final stages of equilibrium solidification. Moreover, additional calculations on increasing levels of Zr suggest that the Al_3Zr phase formation is favored over the Al_3Sc phase.

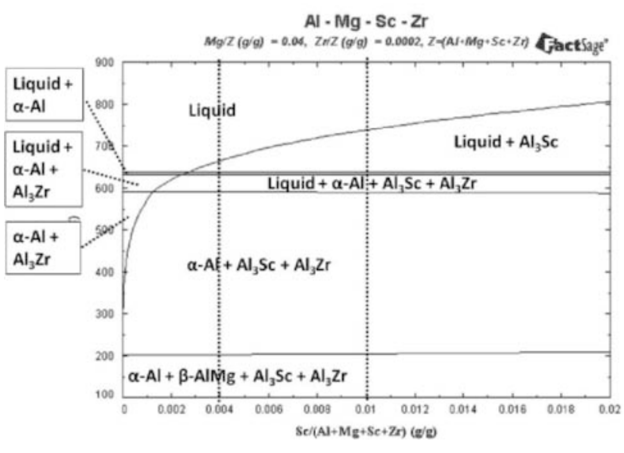

Figure 2. showing isopleths drawn for a constant 0.02 wt.% Zr level, for varying (0-2 wt.%) scandium compositions.

Microstructural Characterization

The optical images for strip cast samples are given in Figure 3.a and b. The images exhibit polygonal phases with grain sizes of 10-20µm. From the size and morphology of the polygonal particulates, it can be stated these are the primary phases formed from the liquid state. In addition to the polygonal phases, small amounts of grain boundary phases are present. No significant segregation of phases was observed throughout the structure.

SEM/EDS mapping conducted mainly on the polygonal particulates as well as the thin grain boundary phases shows that

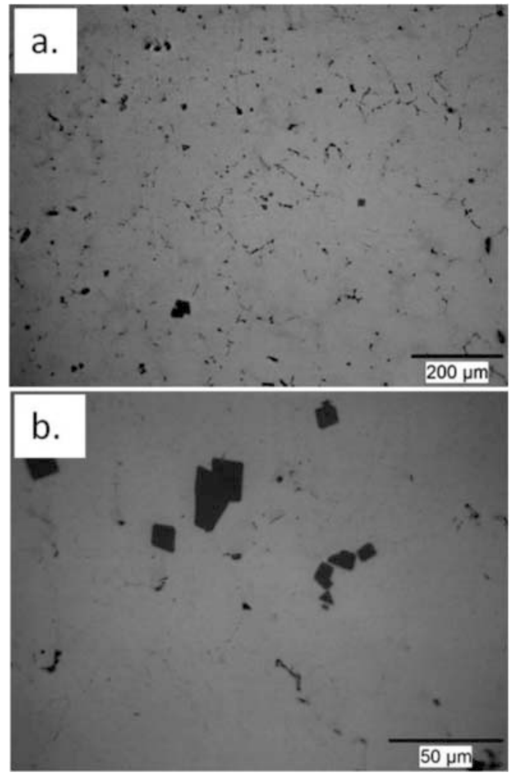

Figure 3.a and b exhibit typical optical micrographs of strip cast Al-Mg-Sc-Zr alloy.

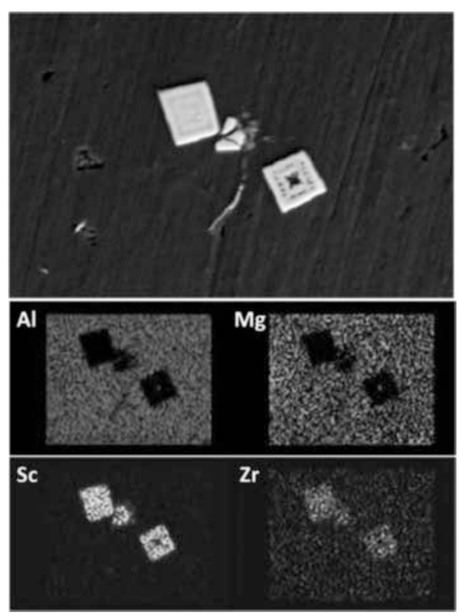

Figure 4. EDS maps of polygonal phases for Al, Mg, Sc and Zr.

Sc and Zr concentrate on the polygonal phases and Mg deposits on the thin grain boundary phases (Figure 4). On the other hand, since the matrix is mainly aluminum, EDS-mapping cannot be used for determining aluminum concentration profiles.

In order to observe the variation in aluminum levels, EDS point analysis was conducted on the polygonal phases, as well as on the matrix. The EDS point analysis results are shown in Table II. The molecular formula determined for the primary phases can be given as $Al_3(Sc_{1-x},Zr_x)$. This result is consistent with the literature [2, 3, 7]. Moreover, Mg is mainly dissolved in the α-aluminum matrix. There is also small amounts of Mg dissolved in grain boundary phases (β-Al-Mg). Additionally, around 0.3 wt.% Sc remained in supersaturation, in the α-Al matrix, during solidification. The solubility limit of Sc in Al is stated to be around 0.4 wt.% at 660°C and drops to 0.07 wt.% at 500°C [7]. Thus, due to high cooling rates, the scandium content in the aluminum matrix remained high. This result was anticipated, owing to high solidification rates in horizontal belt strip casting that are significantly higher than those required for equilibrium cooling conditions.

Table II. Semi-quantitative EDS Point Analysis Results

Region	Al (wt.%/at%)	Sc (wt.%/at%)	Mg (wt.%/at%)	Zr (wt.%/at%)
1	64 / 76.5	29.6 / 21.3	-	6.4 / 2.3
2	62.3 / 75.3	30.6 / 22.2	-	7.1 / 2.6
3	94.9 / 94.6	0.3 / 0.2	4.7 / 5.2	-

** Regions 1 and 2 are polygonal phases; Region 3 is the matrix.*

EBSD analysis was conducted on the cross-section of the strip in longitudinal direction. A schematic of the section used for EBSD analysis, and the grain structure obtained is shown in Figure 5. Average grain size measured by the linear intercept method was found to be around 17 µm ± 4. It was observed that there was a small degree of variation in grain sizes and shapes.

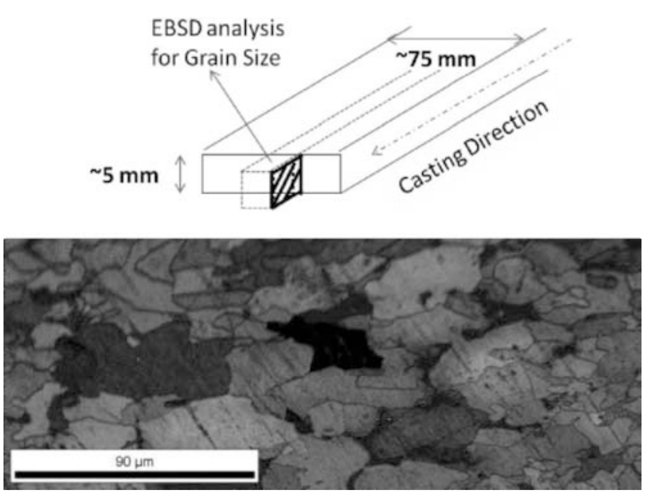

Figure 5. Schematic showing the surface used for EBSD analysis and the grain structure obtained.

Surface Quality

In this study, a graphite coating was applied to the moving steel belt of the pilot scale caster, in order to decrease the negative effects of air pockets on the quality of the bottom surface of the cast strips. The beneficial effect of graphite coating for improving bottom surface quality of strips is mentioned in an earlier study [10]. However, lower cooling rates were observed where casting on graphite coated belts as compared to the castings without graphite coatings.

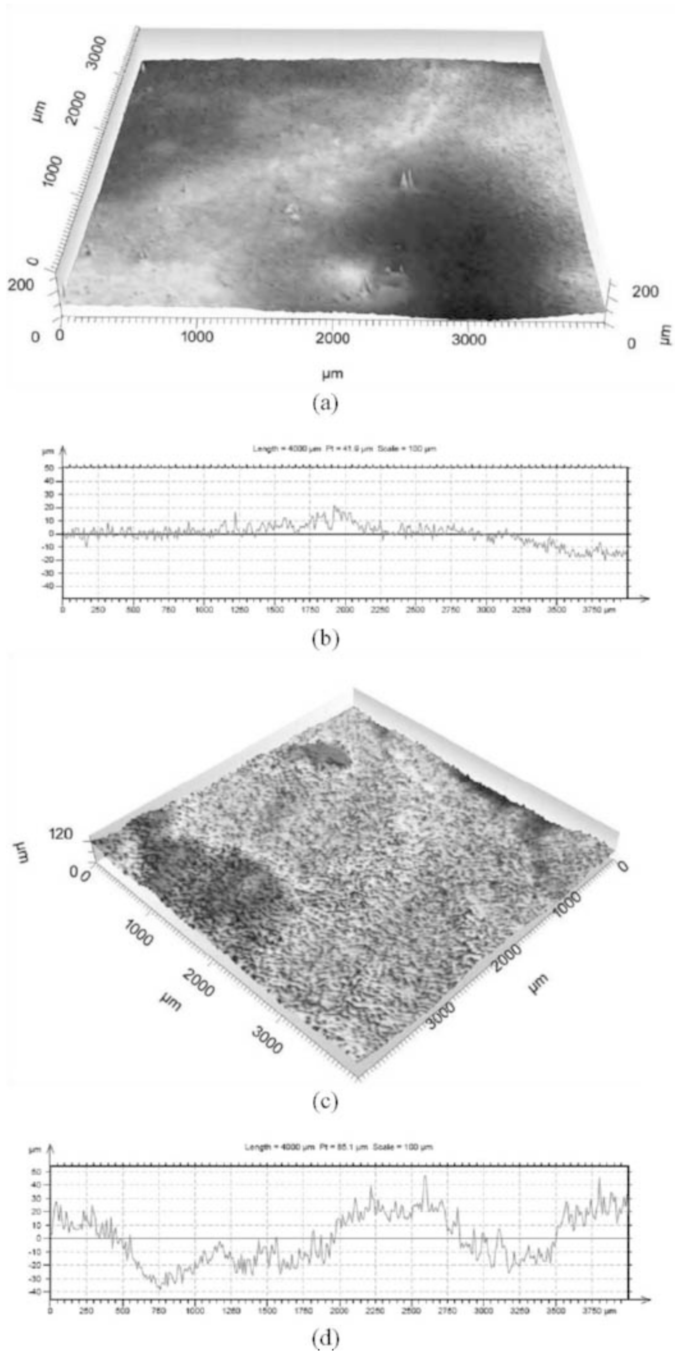

Figure 6. 3D profilometry results for bottom surface of strips; (a) and (b), and for the top surface of strips; (c) and (d).

3D profilometry images for the bottom surface of the strips are given in Figures 6a and 6b. No sign of air pockets was observed, hence the quality of bottom surface of strips is excellent. However, as the top surface solidified in open air, the roughness of the top surface of the strips is higher as shown in Figs. 6c and 6d. Note the small protuberances visible on the bottom surface of the strip, where the first contact was established between the molten metal and the cooling steel substrate. This leads to rapid heat transfer in those locations and to the initiation of nucleation of solid material.

Hardness

Hardness values obtained for strip cast samples are in the range of 72-75 HV (Table III). The obtained values are higher than the hardness values stated (~65 HV) for a conventional casting of similar composition (Al-4.11Mg-0.26Sc-0.14Zr) [3]. The higher hardness values determined in the present study are related to the smaller grain sizes resulted from higher cooling rates. Moreover, the variation in hardness values is high, probably due to the presence of hard primary $Al_3(Sc_{1-x},Zr_x)$ phases.

Table III. Hardness Vickers (HV) Values Determined for Strip Cast Alloys

Alloy	**Hardness (HV)**	**Standard Deviation**
1	*71.5*	*5.3*
2	*72.4*	*4.1*
3	*74.1*	*5.0*

Summary

The capability of HSBC technology was evaluated for the casting and processing of Al-Mg-Sc-Zr alloys through detailed micro-structural characterization, as well as surface roughness and mechanical measurements. A uniform microstructure across the thickness of strip-products was observed. It was found that primary $Al_3(Sc_{1-x},Zr_x)$ phases form from the liquid state and magnesium is mainly present in the alpha matrix. Due to high cooling rates, some Sc also remained in a supersaturated state within the α-Al matrix. Furthermore, 3D profilometry results exhibit that the bottom surface of the strips possess a high surface quality. Preliminary mechanical results of as-cast strip indicate that strip-cast alloys will have higher hardness values compared to conventional cast alloys, owing to smaller grain sizes. Future work will focus on the effects of heat treatments on the final mechanical properties of strip-cast, heat treated alloys.

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