MICROSTRUCTURE EVOLUTION AND MECHANICAL PROPERTIES OF AL-1.94MN-0.5CU ALLOY PRODUCED BY DIRECTIONAL SOLIDIFICATION

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Abstract- In this investigation, Al-1.94Mn-0.5Cu (wt.%) alloy was directionally solidified at different solidification rates varying from 8.3 to 978 □m/s at a constant temperature gradient (7.1 K/mm). The microstructure was analyzed by optical microscopy and scanning electronic microscopy. Especially, cell-dendritic transition was detected for low solidification rate (8.3 □m/s). Then with increasing solidification rate, the microstructure is completely converted to a dendritic form. The microhardness increased from 470 to 520 MPa and the tensile strength increased from 109 to 145 MPa with increasing the solidification rate from 8.3 to 978 □m/s. Exponent values of the V for the microhardness and tensile strength were calculated as 0.04 and 0.06, respectively. Fracture surface images of the studied alloys were analyzed depending on solidification rate. These fracture surfaces exhibited a lot of small dimples, a characteristic of ductile fracture. Many micro-cracks start from these voids and dimples. The mode of fracture significantly changed from ductile to less ductile with the increase of the solidification rate.

Index Terms- Directionally solidification, microstructure, microhardness, tensile strength, fracture.

I. INTRODUCTION

Aluminum and aluminum alloys are used in industry because of their resistance characteristics, corrosion resistance, low specific weight, conductance of electricity, and heat and flexibility. These properties make them valuable for use in various industrial applications, and researchers have been actively exploring new application for these alloys [1–4].

The most prominent feature of aluminum in engineering applications and everyday life is its lightness. In addition, alloying elements in aluminum improve its strength and stiffness, properties which are superior compared to other metals. Al–Mn alloy is made from cheap elements but shows good magnetic properties superior to the well-known Alnicos and hard ferrites [5]. In addition, Al–Mn alloy shows good machinability and corrosion resistance [5]. Alloying copper in aluminum improves its strength and increases its hardness. For these reasons, research studies on Al–Mn, Al–Cu and Al–Mn–Cu great interest.

The mechanical and thermo physical properties of a material depend on not only the selection of alloying elements but also the production technique employed. The directional solidification technique by Bridgman-type equipment is one of the most important techniques for producing crystal growth that is widely utilized in engineering. Aluminum and aluminum alloys, more so than other alloys, are prone to having possible casting errors, such as cracks and distortions, due to volume shrinkage depressions. These errors can be minimized by using Bridgman's technique as known The Controlled Solidification Technique.

The purpose of this work is to experimentally investigate the relationships between growth velocity (V) and the microstructure parameters (λ) and also mechanical properties (HV, σ) in the directionally solidified Al-1.94Mn-0.5Cu alloy.

II. EXPERIMENTAL PROCEDURE

A. Sample Preparation and Solidification

In this work, Al-1.94Mn-0.5Cu ternary alloy was prepared in a vacuum atmosphere by using aluminum, manganese and copper of purity of 99.99%. After allowing time for melt homogenization, the molten alloy was poured into 10 graphite (250 mm in length, 4 mm ID and 6.35 mm OD) held in a specially constructed hot filling furnace at about 50 K above the melting point of the alloy. The molten metal was then directionally solidified from bottom to top to ensure that the crucible was completely full.

Then, each sample was positioned in a Bridgman type furnace in a graphite cylinder (300 mm in length 10mm ID and 40 mm OD). In this technique, the sample was heated about 200 K above the melting temperature and the sample was then growth by pulling it downwards by synchronous motors.

After 10-12 cm steady state growth, the samples were quenched by rapidly pulling it down into the water reservoir. The temperature of water in the reservoir was kept at 283 K with accuracy of ± 0.1 K by using a digital heating / refrigerating circulating bath (model 9102; Poly Science). The sample temperature was also controlled to accuracy of ±0.1 K using a Eurotherm 2604 type controller. Solidification of the samples was carried with different growth velocities (V=8.3-978 □m/s) at a constant G (7.1 K/mm).

B. Measurement of Growth Velocity and Temperature Gradient

Three temperatures in the samples were measured by K-type thermocouples which were fixed within the sample with spacing of 10-20 mm. All the thermocouple's ends were then connected the measurement unit consists of data-logger and computer. The cooling rates were recorded with a data-logger via computer during the growth. When the solid/liquid interface was at the second thermocouple, the temperature difference between the first and second thermocouples (ΔT) was read from data-logger record. The time taken for the solid-liquid interface phases the thermocouples separated by known distances was read from data-logger record. Thus, the value of growth velocity (V= ΔX / Δt) for each sample was determined using the measured value of Δt and known value of ΔX. The temperature gradient (G =ΔT/ΔX) in the liquid phase for each sample was determined using the measured values of ΔT and ΔX.

C. Metallographic Examination

The quenched samples were removed from the graphite crucible and 3 cm in lengths from the top and bottom were cropped off and discarded. Then the rest of the samples ground to observe the solid-liquid interface and the longitudinal section, which included the quenched interface was separated from the specimen. This parts of specimens were mounted in a cold-setting epoxy-resin. The longitudinal and transverse sections were wet-ground down to 2500 grit and mechanically polished using 6-□m, 3-□m, 1-□m, and 0.25-□m diamond paste. Finally, the samples were etched with an acid solution (5 ml hydrofluoric acid, 95 ml distilled water) to reveal the microstructure.

The microstructures of samples were characterized from both transverse and longitudinal sections of samples using LEO scanning electron microscopy (SEM).

D. The Measurement of Microhardness and Tensile Strength

The mechanical properties of any solidified materials are usually determined with hardness test, tensile strength test, compressive strength test, ductility test, etc. Since true tensile strength testing of solidified alloys gave inconsistent results with a wide scatter due to the strong dependence on the solidified sample surface quality, the mechanical properties were monitored by hardness testing, which is one of the easiest and most straightforward techniques.

Microhardness measurements in present work were made with a DuraScan model hardness measuring test device using a (10-50 g) load and a dwell time of 10 s giving a typical indentation depth about 40-60 □m, which is significantly smaller than the original solidified samples. The minimum impression spacing (center to edge of adjacent impression) was about 3 times the diagonal and was located at least 0.5 mm from the edge of sample. The microhardness was the average of at least 30 measurements on the sample.

The tests of tensile strength were performed at room temperature with a Shimadzu AG-IS universal testing machine.

The measurements of tensile strength were made at room temperature at a strain rate of 10^{-3} s^{-1} with a Shimadzu AG-XD universal testing machine. The round rod tensile and compressive samples with diameter of 4 mm and gauge length of 15 mm were prepared from directionally solidified rod samples with different growth velocities (V=8.3-978□□m/s) at a constant G (7.1 K/mm).

III. RESULTS

A. Effect of Growth Velocity on Eutectic Spacing

Variations of dendritic spacing (λ) with the growth velocity (V) at a constant G (7.1 K/mm) is given in Fig. 1. As shown Fig. 1, growth velocity increases, the dendritic spacing decreased from 183 to 18 □m. Especially, cell-dendritic transition was detected for low solidification rate (40 □m/s). Then with increasing solidification rate, the microstructure is completely converted to a dendritic form.

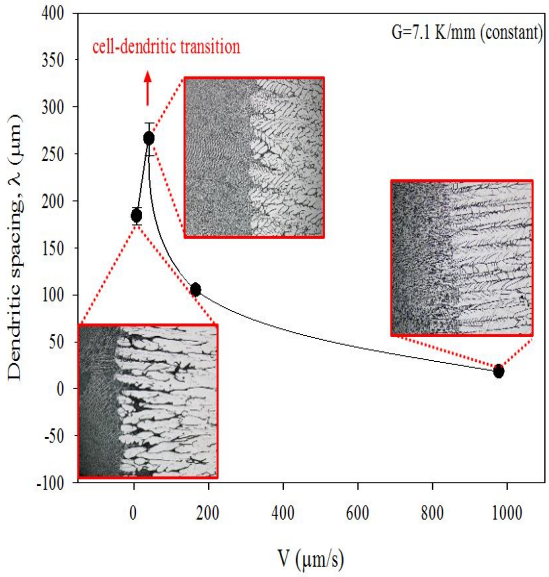


Fig. 1. Variation of dendritic spacing as a function growth velocity.

B. The Effect of Growth Velocity on Microhardness and Ultimate Tensile Strength

As mentioned above, Al-Mn-Cu bulk samples were directionally solidified under constant temperature gradient (G=7.1 K/mm) with different growth velocity (V=8.3-978 □m/s). It can be seen from Fig. 2 that an increase growth velocity leads to an increase in the microhardness and decrease dendritic spacing up to dendritic-cell transition region. Dependence of the HV on the V was determined by using linear regression analysis and it found that $HV=(51.6)V^{0.02}$.

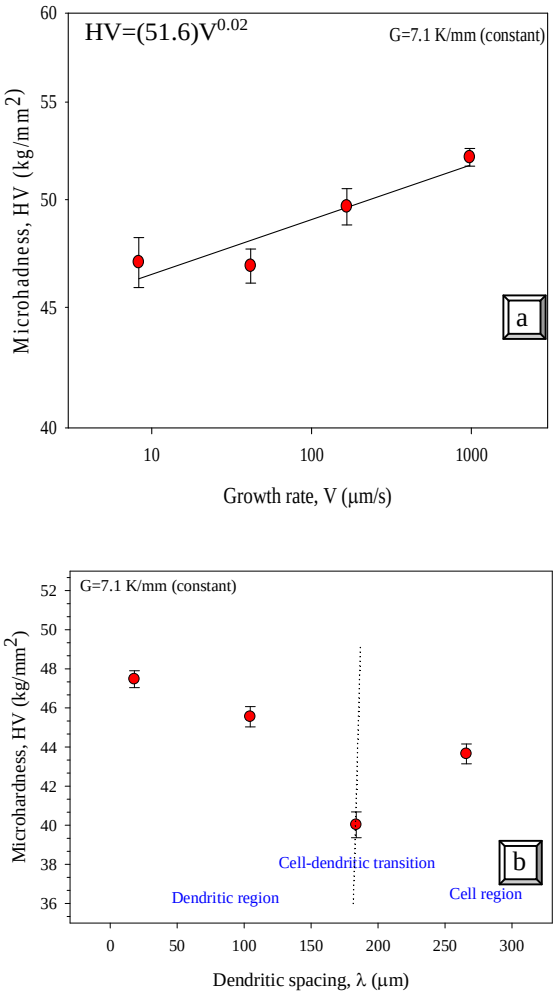
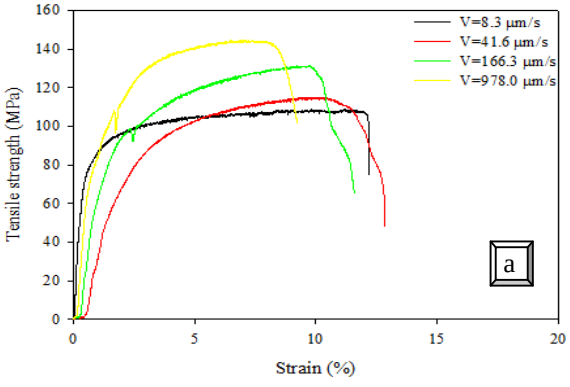


Fig. 2. a) Microhardness versus growth rate b) microhardness versus dendritic spacing.

Besides, it is found that increasing growth rate from 8.3 □m/s to 978 □m /s, microhardness increases from 47 kg/mm^2 to 52 kg/mm^2 and also decreasing dendritic spacing from 183 □m to 104 □m, microhardness increases.

Typical strength-strain curves of Al-Mn-Cu alloy are shown in Fig. 3 for different growth velocity. As can be seen from Fig. 3, ultimate tensile strength□□UTS, □□ values are increased with increasing V, but dendritic spacing are increased.



As can be seen from Figs. 3, the values of □ increase with increasing V. It was found that increasing V from 8.3 □m/s to 978 □m/s, the UTS values increase from 109 MPa to 145MPa. The exponent value of V is found to be 0.06.

C. Fracture Surface behavior

The mechanical properties of materials are related directly to the fracture mechanism, especially during microscopic fracture events and the crack extending process.

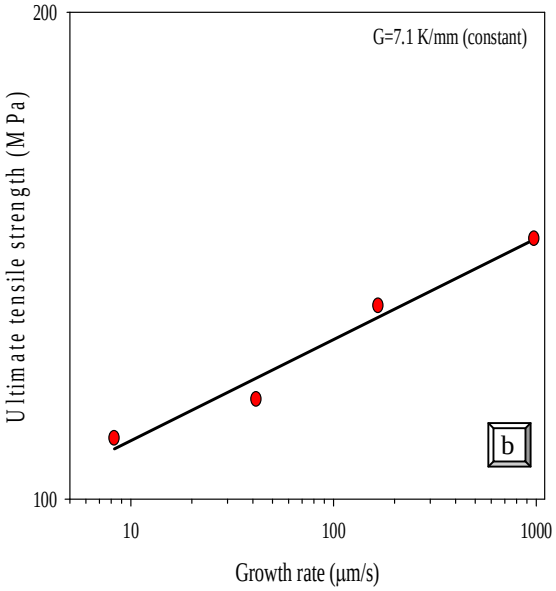


Fig. 3. a) Tensile strength versus strain b) Ultimate tensile strengths versus growth rate.

Therefore, quantitative fractography plays an important role in material research by using the scanning electron microscope.

Yet even though the fracture can be classified as brittle when plastic deformation is confined to the fracture path, the micro mechanism of the fracture may be ductile.

In fact, many fractures occur by a ductile micro mechanism, even though the macroscopic fracture is termed brittle with little or no overall plastic deformation or macroscopic work. In this sense, the terms brittle and ductile fracture are most clearly defined in a macroscopic context. In this study, fracture surface images of the studied alloys were analyzed depending on the composition.

Fig. 4 shows the macroscopic appearance of fracture surfaces of the Al-1.94Mn-0.5Cu alloy. These fracture surfaces exhibited a lot of small dimples, a characteristic of ductile fracture. There are some large voids and dimples marked with dark arrows. Fig. 4 shows the morphology of the microstructure on the ductile manner fracture surface. Secondary cracks are present in the dendritic spaces.

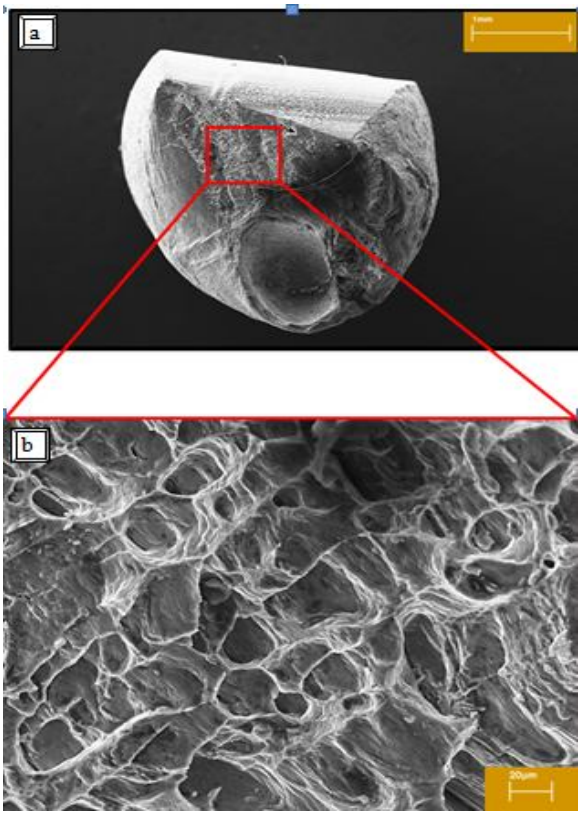


Fig. 4. SEM fractographs showing tensile fracture surface of Al-Mn-Cu dendritic alloy; (a) general morphology of the fracture surface of Al-Mn-Cu alloy, (b) high magnification view of fracture surface

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