MICROSTRUCTURE, MICROHARDNESS AND TENSILE PROPERTIES OF AL-MN-0.5SI ALLOY PRODUCED BY DIRECTIONAL SOLIDIFICATION

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Abstract—The directional solidification process of ternary Al-1.94Mn-0.5 Si eutectic alloy within a wide growth velocity range from 8.3 to 978 μm/s was accomplished at a constant temperature gradient of 4.9 K/mm. The microstructures of produced samples were characterized by using optical microscopy (OM), scanning electron microscopy (SEM) and Energy dispersive x-ray analysis (EDX). Dendritic microstructures were observed in the directionally solidified samples. The dendritic spacing tends to decrease with increasing growth velocity. As growth velocity increases, the dendritic spacing decreased from 160 to 68 □m. Microhardness and tensile strength at room temperature were examined by tensile tests. It was found that the microhardness and ultimate tensile strength increased with increasing growth velocity, which ranged from 8.3 to 978 μm/s. Exponent values of the V for the microhardness and tensile strength were calculated as 0.05 and 0.09, respectively. Fracture surface images of the studied alloys were analyzed depending on growth velocity. The fracture mode transforms from ductile form to less ductile form with the increase of the growth velocity.

Index Terms— Fracture, microhardness, microstructure, tensile strength, Ternary eutectic alloy,

I. INTRODUCTION

The production and application of aluminum alloys has increased considerably in the past few decades because of their good strength-to-weight ratios. Their use is justified in a variety of processes where a light and corrosion-resistant material is needed. The progress of aluminum alloys is leading to better mechanical properties and to improvements in the relatively poor strength and heat resistance of classical aluminum alloys [1]. The properties of an alloy depend on its chemical composition, structure and microstructure, which in turn depends on a variety of production conditions. Thermal treatment (quenching in our case) is one of the influences that affects the microstructure. The alloy investigated was an Al-Mn-Be alloy, one of less-investigated alloys so far. Al-Mn alloys are suited for the manufacturing of metastable quasicrystalline materials with rapid solidification. In the past few years, it was discovered by Song et al. [3] that the addition of beryllium to an Al-Mn alloy reduces the solubility of manganese in an aluminum solid solution and leads to the formation of quasicrystals and quasicrystal approximants at lower cooling rates. In practice, for the production of quasicrystals other aluminum based alloys are also used,

for example, Al-Cu-Fe, Al-Cu-Cr, Al-Mn-B, Al-Cr-B, and Al-Si-Mn [4–5].

Al-Mg and Al-Mn alloys are widely used, and the hardening effect of Mg and Mn in solid solution has been studied (e.g. [6]). Small amounts of Si usually exist in many commercial alloys, and may affect the mechanical properties. Tensile [7] and hot deformation experiments [8] of binary Al-Si alloys, and theoretical calculations [9] indicate that Si has a weak hardening effect. However, the effect of the combination of multiple elements on strength is not well known. The total increase of strength is not expected to be linearly dependent on each component [10]. The aim of this work was to investigate the hardening effect of Si addition in high purity Al-Mn binary alloys to study the influence of multiple elements on strength.

These properties also lead to the association of aluminum and its alloys with transportation, particularly with aircraft and space vehicles, with construction and building, containers and packaging and electrical transmission lines. It is known that the mechanical properties of metallic materials are affected by their morphology. The mechanical properties of directional solidified Al-base alloys, which are important commercial materials, have been reported in several investigations [11] but the results differ from each other. The microstructure evolution during solidification depends on the alloy characteristics and primarily is a function of the temperature profiles at the solidification interface. When a metallic alloy is solidified, the most frequently observed solid morphology is the dendritic microstructure [12]. The solidification parameters of alloys are the temperature gradient (G) and growth velocity (V). The solidification parameters of alloys directly affect the microstructure of the alloy systems, and also significantly influence their mechanical behaviors. Hence, the effects of applied solidification and microstructure parameters on mechanical behavior have been studied intensively [15], [16].

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-Mn-Si eutectic alloy.

II. EXPERIMENTAL PROCEDURE

A. Sample Preparation and Solidification

In this work, Al-1.94Mn-0.5 Si ternary alloy was prepared in a vacuum atmosphere by using aluminum, manganese and silicon 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 (see Fig.1) 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.

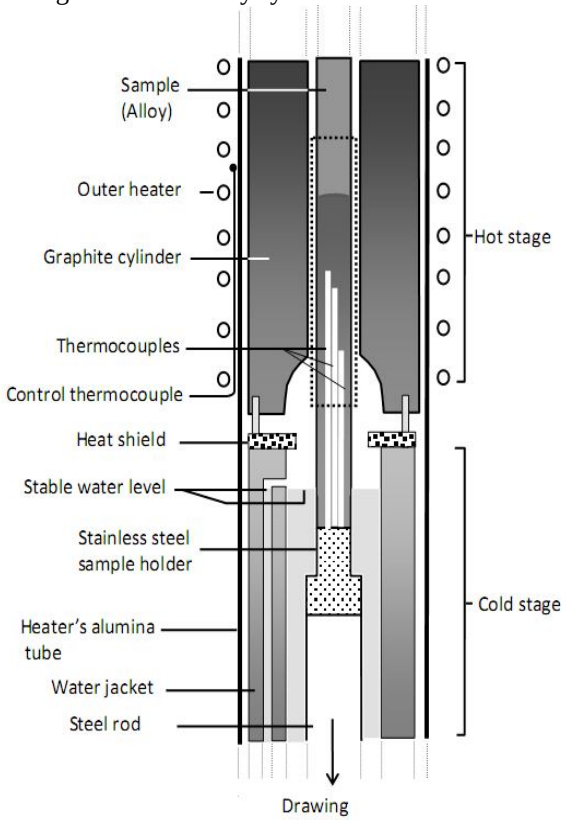


Fig. 1. The details of Bridgman type directional solidification furnace.

After 10-12 cm steady state growth, the samples were quenched by rapidly pulling it down into the water reservoir. The melting point of Al-Mn-Si ternary alloy is about 944.7 K. The temperature of water in the reservoir was kept at 278 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 (4.9 K/mm).

B. Measurement of Growth Velocity and Temperature Gradient

As shown in Fig. 1 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 ($V = \Delta X / \Delta t$) for each sample was determined using the measured value of Δt and known value of ΔX. The temperature gradient ($G = \Delta T/\Delta X$) 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 (see Fig.2). 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

One of the purposes of this investigation was to obtain the relationships among growth rate, rod spacings, 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.

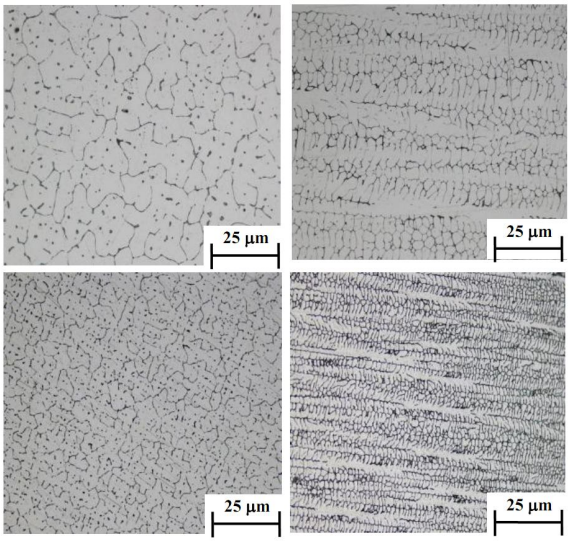


Fig. 2. Typical images of the growth morphologies of directionally solidified Al-Mn-Si alloy at a constant G (4.9 K/mm).

The Vickers hardness (HV) is the ratio of a load applied to the indenter to the surface area of the indentation. This is given by

$$HV = \frac{2P\sin(\theta/2)}{d^2} \qquad (1)$$

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 data collected from the tensile test can be analysis using the following formula to determine the strength (□);

$$\sigma = \frac{F}{A} \qquad (2)$$

where □ is the strength in N/mm^2 (or MPa), F is the applied force (N), A is the original cross sectional area of the sample. 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 (4.9 K/mm).

III. RESULTS

A. Effect of Growth Velocity on Dendritic Spacing

Variations of dendritic spacing (λ) with the growth velocity (V) at a constant G (4.9 K/mm) is given in Fig. 3. The variation of □ versus V can be given the proportionality equation as,

$$□□=k_1V \qquad (3)$$

where k_1 is constant and a is an exponent value of growth velocity. As shown Fig. 2 and Fig. 3, growth velocity increases, the dendritic spacings decreased from 160 to 68 □m. The relationships between the eutectic spacing and growth velocities were determined as□□=27.3 $V^{-0.39}$ by using linear regression analysis. The exponent value 0.43 is in good agreement with the range values of 0.35-0.45 obtained by different researchers [15], [17]-[19].

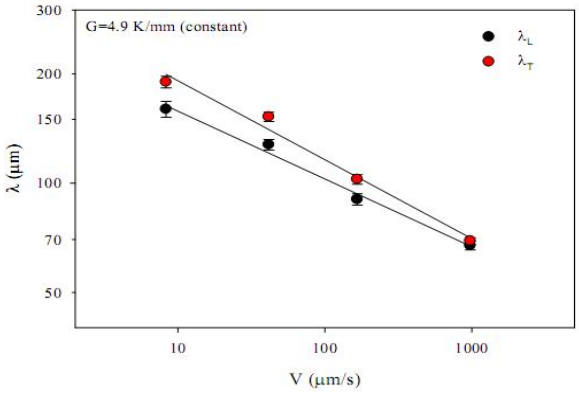


Fig. 3 Variation of eutectic spacings as a function growth velocity

B. The Effect of Growth Velocity on Microhardness

As mentioned above, Al-Mn-Si bulk samples were directionally solidified under constant temperature gradient (G=4.9 K/mm) with different growth velocity (V=8.3-978 □m/s). It can be seen from Fig.4 that an increase growth velocity leads to an increase in the microhardness. Dependence of the HV on the V and □ were determined by using linear regression analysis and the relationship between them can be expressed by the following equations as,

$$HV=k_2\,V^{b} \qquad (4)$$

$$HV=k_3\,□^{c} \qquad (5)$$

where k_2 and k_3 are constant, b and c are the exponent values of the growth velocity and eutectic spacing, respectively. As can be seen from Figs. 4 and 5, the microhardness values increase with the increasing V values and decreasing with the increasing□□□values.

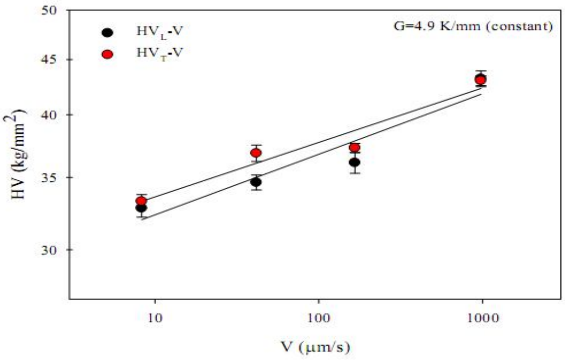


Fig. 4 Variation of microhardness, HV *vs*.V

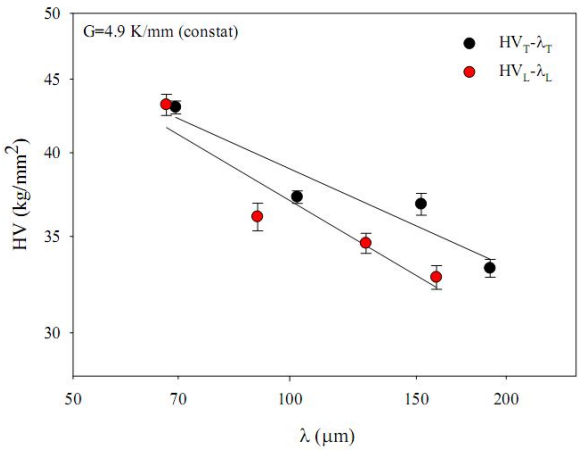


Fig. 5 Variation of microhardness, HV *vs.* λ

It is found that increasing growth rate from 8.3 □m/s to 978 □m /s, microhardness increases from 33 kg/mm^2 to 43 kg/mm^2 and also decreasing dendritic spacings from 190 □m to 69 □m, microhardness increases. The average exponent values of V and □ for HV in the directionally solidified Al-Mn-Si alloy were found to be 0.06 and 0.07 for longitudinal and transverse sections, respectively in this work. These exponent values relating to V and □ obtained in present work is generally in a good agreement with the exponent values obtained in previous experimental works [15], [17]-[19] under similar solidification conditions.

C. The Effect of the Growth Velocity on Ultimate Tensile Strength

Typical strength-strain curves of Al-Mn-Si alloy are shown in Fig. 6 for different growth velocity. As can be seen from Fig. 6, ultimate tensile strength□□UTS, □□ values are increased with increasing V, but dendritic spacings are increased with ultimate tensile strength□decreased.

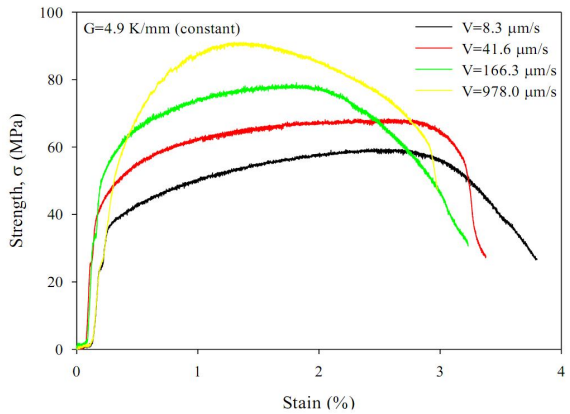


Fig. 6 Typical strength-strain curves of the Al-Mn-Si alloy under constant *G* (4.9 K/mm) at different *V* (8.3-978 μm/s).

Fig. 7 shows the variation of the □ with the V. The dependence of □ on V, can be represented as,

$$\sigma = k_4 V^d \qquad (6)$$

As can be seen from Fig. 7, 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 59.46 MPa to 91.06 MPa. The exponent value of V is found to be 0.09.

F. 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. 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.

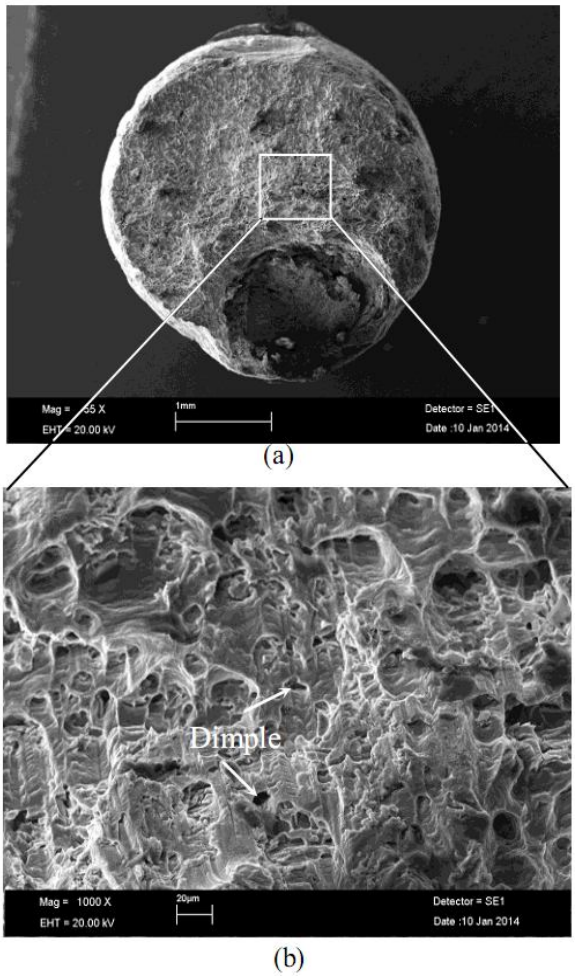


Fig. 8. SEM fractographs showing tensile fracture surface of Al-Mn-Si eutectic alloy; (a) general morphology of the fracture surface of Al-Mn-Si alloy, (b) high magnification view of fracture surface.

Figure 8 shows the macroscopic appearance of fracture surfaces of the Al-Mn-Si 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. Figure 8 shows the morphology of the microstructure on the ductile manner fracture surface. Secondary cracks are present in the dendritic spaces.

ACKNOWLEDGMENT

This project was supported by the Scientific and Technical Research Council of Turkey (TUBİTAK) under contract no. 212T130.

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