STRUCTURES AND MECHANICAL PROPERTIES OF RAPIDLY SOLIDIFIED Al-5~13%Mg-2~13%Si TERNARY ALLOYS

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ABSTRACT Rapidly solidified P/M materials were prepared for Al-Mg-Si ternary alloys of higher alloying additions than the commercial Al-Mg-Si alloys. Rapid solidification was performed by argon gas atomization and subsequent splat quenching on a water-cooled copper roll. The rapidly solidified flakes were consolidated to P/M materials by cold pressing, vacuum degassing and hot extrusion at 673K with a reduction of 25:1. Cast ingots of these alloys were also hot-extruded under the same conditions to the I/M reference materials. Tensile strength of the as-extruded P/M materials is higher than that of the I/M counterparts. The tested alloys were grouped into two classes according to the changes of hardness and tensile strength of the P/M materials with increasing Mg+Si content. The alloys containing excess Mg to the Mg_2Si composition showed higher hardness and tensile strength than those without excess Mg at the same Mg+Si content. It is considered that both Mg solid solution and dispersion of Mg_2Si particles were contributing to the strength increases in the P/M materials. The highest tensile strength of 516 MPa at room temperature was obtained in the P/M material of Al-13%Mg-4%Si alloy.

Keywords: *rapid solidification, powder metallurgy, aluminum-magnesium-silicon alloy, mechanical property, microstructure*

1. INTRODUCTION

Al-Mg-Si alloys are in commercial use as both wrought and cast materials. Although Si is added beyond its maximum solid solubility to the cast Al-Si-Mg alloys for the benefit of castability, all the wrought alloys are in the composition range within the ternary solid solubility. However, directional solidification [1], high pressure casting [2], rolled materials from cast ingots [3] and supeplastic properties of rolled materials [4] have been studied on the alloys near the Al-Mg_2Si quasi-binary eutectic composition, that is, Al-8.15mass%Mg-4.75mass%Si [5]. Rapid solidification and P/M processing is effective to the refinement of microstructures. Hence, it is expected that materials of higher strength can be obtained for the alloys with high volume fractions of second phase particles by rapid solidification. In this work, rapid solidification and P/M processing have been applied to alloys around the Al-Mg_2Si quasi-binary eutectic composition. Nine alloys in the composition range of Al-5~13mass%Mg-2~13mass%Si were rapidly solidified by argon gas atomization and subsequent splat quenching on a water-cooled copper roll. The rapidly solidified flakes were consolidated to P/M materials by cold pressing, vacuum degassing and hot extrusion at a reduction of 25:1. Cast ingots of the same alloys were also hot-extruded under the same conditions to the I/M reference materials. Structures and mechanical properties of the P/M materials were examined and compared to the I/M counterparts.

2. EXPERIMENTAL PROCEDURES

Nominal and analyzed compositions of the tested alloys are listed in Table 1. The nominal composition is plotted on the liquidus surface diagram of the Al-Mg-Si ternary system in Fig. 1. As shown in this figure, four alloys (A,B,C,D) are on the monovariant eutectic line including one (D) at the ternary eutectic composition, three alloys (F,G,H) in the hyper-eutectic range and two (E,I) in the hypo-eutectic compositions. Three alloys (B,E,F) are on the Al-Mg_2Si quasi-binary line including one (B) at the quasi-binary eutectic composition. Rapid solidification was carried out by using an apparatus reported elsewhere [6]. Alloy melt which was held at a temperature approximately 100K above the liquidus was rapidly solidified to flakes by argon gas atomization and subsequent splat quenching onto a water-cooled copper roll. About 1 kg of flakes were prepared for each alloy. The flakes were consolidated to P/M materials by cold pressing, vacuum degassing and hot extrusion. Vacuum degassing was done at 573K for 7.2ks. Hot extrusion was carried out at 673K at a reduction of 25:1 and round bars of 7mm in diameter were obtained. The cast ingots of the same alloys were also hot-extruded to the reference I/M materials under the same conditions after soaking at 723K for 86.4 ks.

Microstructures were observed by OM for the RS flakes, P/M and I/M materials. Hardness of the flakes, as extruded P/M and I/M materials were measured at more than 10 points and the averaged values were obtained. Tensile tests of the as-extruded P/M and I/M materials were carried out at room temperature, 473 and 573K. The results are shown by the average of more than 3 tensile tests. The test piece was held at the test temperature for 300s. For as extruded P/M and I/M materials, consituent phases and solute Mg content were examined by X-ray diffraction.

Table 1: Nominal and chemical composition of test alloys.

Alloy	Nominal Composition (mass%)	Chemical Composition (mass%)
A	Al-10%Mg-3%Si	Al-9.77%Mg-3.04%Si
B	Al-8%Mg-5%Si	Al-8.14%Mg-4.98%Si
C	Al-6%Mg-8.5%Si	Al-5.71%Mg-8.65%Si
D	Al-5%Mg-13%Si	Al-4.81%Mg-13.32%Si
E	Al-5%Mg-3%Si	Al-4.90%Mg-3.16%Si
F	Al-12%Mg-7%Si	Al-11.87%Mg-7.02%Si
G	Al-10%Mg-10%Si	Al-9.05%Mg-9.95%Si
H	Al-13%Mg-4%Si	Al-14.32%Mg-3.24%Si
I	Al-8%Mg-2%Si	Al-8.32%Mg-1.99%Si

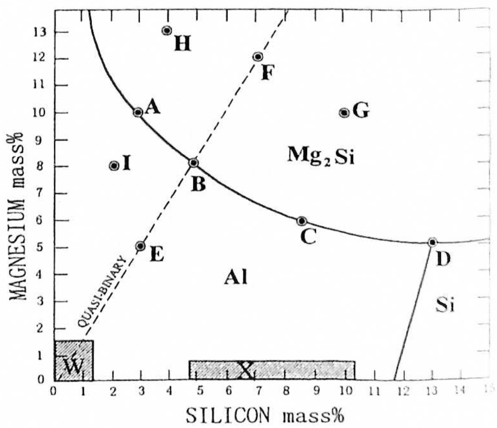

Fig. 1: Test alloys on liquidus diagram of Al-Mg-Si.

3. RESULTS AND DISCUSSION

3.1 Structures and hardness of rapidly solidified flakes

Rapidly solidified flakes of all the alloys show fine dendrite cell structures as shown in Fig. 2 for Alloy C. The average cell size is 3-5 μ m, and cooling rate during solidification is estimated to be in the order of 10^3 K/s. Formation of primary Mg_2Si was suppressed in the alloys of hyper-eutectic compositions.

Hardness of as rapidly solidified flakes is plotted against Mg+Si mass% in Fig. 3. It is clearly seen that hardness increases with increasing Mg+Si content. Highest hardness of 218HV is obtained for Al-10mass%Mg-10mass%Si which contains highest Mg+Si mass%. Second phase particles of a higher volume fraction are formed in an alloy of higher Mg+Si content, and fine second phase particles formed at the cell boundaries by rapid solidification contribute to strengthening of these flakes.

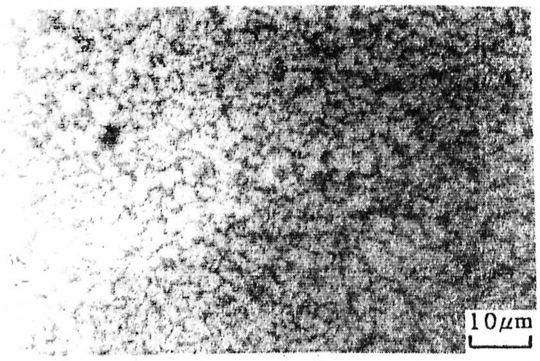

Fig. 2: Microstructures of rapidly solidified flake of Alloy C.

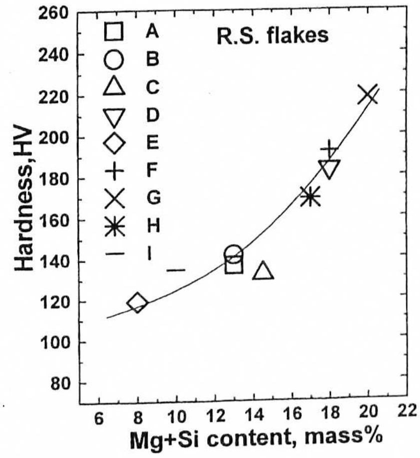

Fig. 3: Hardness of rapidly solidified flakes vs. Mg+Si mass%.

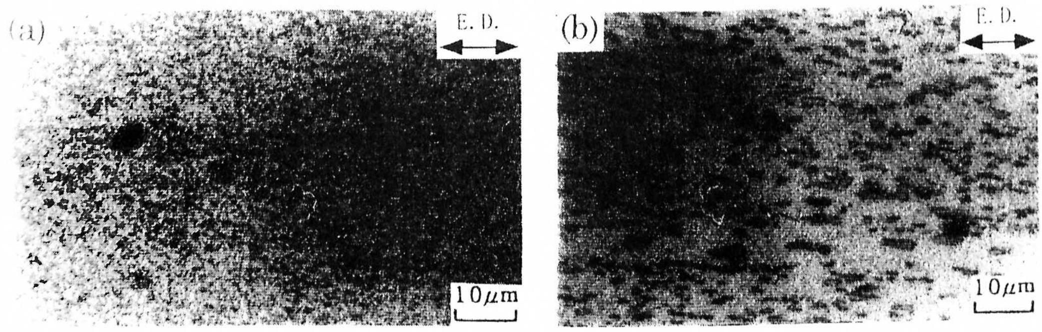

Fig. 4: Microstructures of as extruded P/M (a) and I/M (b) materials of Alloy A.

3.2 Structures and hardness of P/M and I/M materials

As an example, microstructures of as extruded P/M and I/M materials are shown in Fig. 4 for Alloy A. These micrographs were taken on the section parallel to the extrusion direction. After hot extrusion, second phase particles become uniformly distributed in both materials. However, second phase particles in P/M materials are much finer than those in the I/M counterparts. Differences in such microstructures are caused by difference in cooling rate during solidification and rapid solidification is beneficial to refinement of microstructures of the hot extruded materials.

Hardness of as extruded P/M and I/M materials is shown in Fig. 5. Hardness of P/M materials is higher than that of I/M counterparts for all the tested alloys. Hardness of P/M materials is changed from that of rapidly solidified flakes. Highest hardness of P/M materials is observed for Al-13mass%Mg-4mass%Si, whereas highest hardness of flakes is for the alloy containing highest Mg+Si content. Hardness of P/M materials is plotted against Mg+Si mass% in Fig. 6. Hardness values of P/M materials are separated into two curves, an upper curve for the alloys containing excess Mg with respect to the Mg_2Si composition and a lower one for the alloys containing no excess Mg. From X-ray diffraction, the alloys with excess Mg is estimated to contain 5.4 to 6.2 mass% of solute Mg, whereas the other alloys without excess Mg contain 0.6 to 1.6 mass% solute Mg. In the alloys containing excess Mg, second phase particles of Mg_2Al_3, which were considered to be formed by rapid solidification, were subsequently solutionized during hot extrusion. It is thus concluded that solid solution hardening is contributing to the higher hardness of P/M materials of the alloys containing excess Mg.

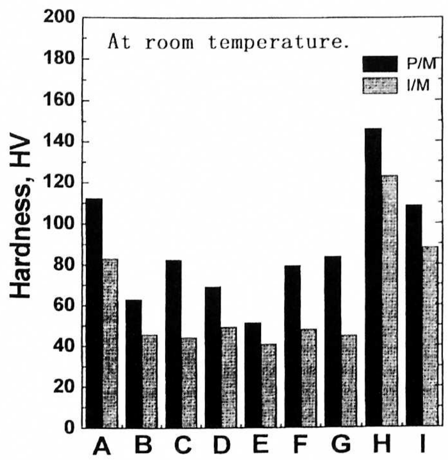

Fig. 5: Hardness of as extruded P/M and I/M materials.

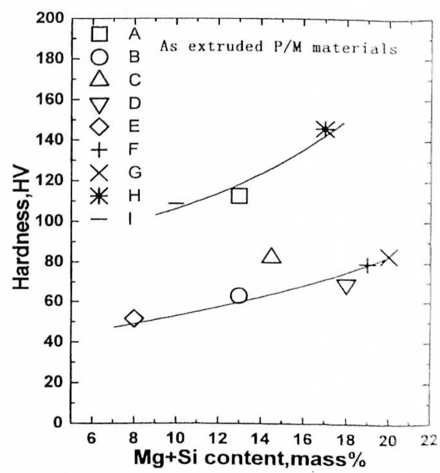

Fig. 6: Hardness of P/M materials vs. Mg+Si mass%

3.3 Tensile properties of P/M and I/M materials

Tensile strength of as extruded P/M and I/M materials at various temperatures is shown in Fig. 7. At room temperature, tensile strength is higher for P/M materials than I/M counterparts thereby effects of rapid solidification is obviously shown. The highest tensile strength of 516 MPa was observed for the P/M material of Al-13mass%-4mass%Si. Tensile strength at room temperature is higher for both P/M and I/M materials for three alloys containing excess Mg to the Mg_2Si composition. Tensile strength drops more remarkably in P/M materials as the test temperature rises to 473K. At 573K, tensile strength of both P/M and I/M materials decreases around 50 MPa regardless of alloy compositions.

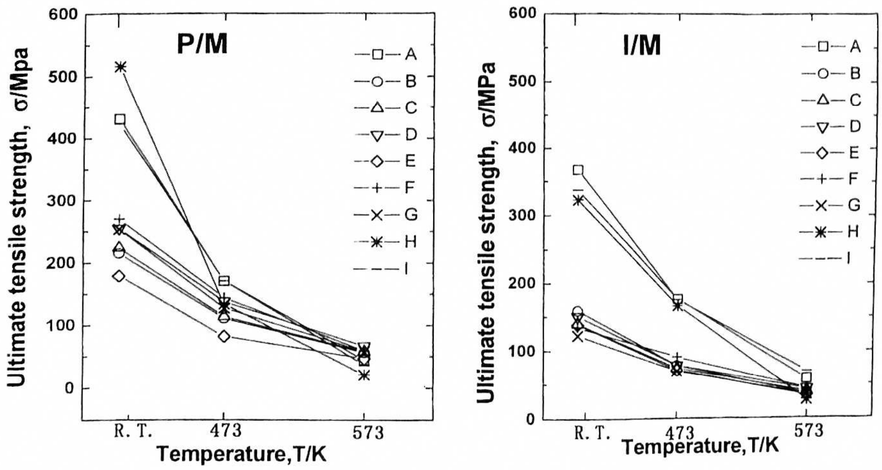

Fig. 7: Tensile strength of P/M and I/M materials at various temperatures.

Tensile elongation increases with rising test temperature for both materials. No distinctive differences in elongation are observed between P/M and I/M materials at each temperature. At room temperature, elongation of Al-13%Mg-4%Si alloy which shows highest tensile strength is lowest for both P/M and I/M materials, 1.8 and 3.9%, respectively. Well balanced tensile properties are observed for the P/M material of Al-8%Mg-2%Si with third highest tensile strength of 423 MPa and elongation of 18%. Highest elongation of 121% is obtained at 573K for the I/M material of Al-13%Mg-4%Si.

Tensile strength of P/M materials is again plotted against Mg+Si mass% in Fig. 8. Just same as for hardness shown in Fig. 6, tensile strength values of P/M materials are separated into two curves, an upper curve for the alloys containing excess Mg with respect to the Mg_2Si composition and a lower one for the alloys containing no excess Mg. Solid solution hardening of Mg is contributing to the higher strength of P/M materials of the alloys containing excess Mg.

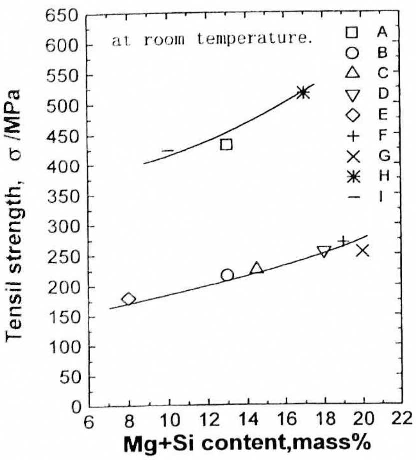

Fig. 8: Tensile strength of P/M materials vs. Mg+Si mass%.

Table 2: Specific modulus and specific strength of P/M materials.

	E (GPa)	D (g/cm^3)	E/D (GPa/g/cm^3)	σ_B/D (MPa/g/cm^3)
A	67.4	2.57	26.20	167.75
B	99.6	2.55	39.01	84.34
C	94.3	2.57	36.68	87.07
D	97.0	2.59	37.52	98.49
E	89.1	2.64	33.72	67.84
F	103.0	2.53	40.74	106.66
G	90.2	2.51	35.88	100.99
H	113.0	2.53	44.65	203.77
I	111.0	2.60	42.77	163.17

Elastic modulus, density, specific modulus and specific strength of as extruded P/M materials are listed in Table 2. Elastic modulus is increased from that of pure aluminum with increasing Mg+Si content. Elastic modulus of Al-13%Mg-4%Si is about 60% higher than that of pure aluminum. Density decreases with increasing Mg+Si content. The lowest density of 2.514 g/cm^3, which is 7% lighter than pure aluminum, is obtained for Al-10mass%Mg-10mass%Si. Increases in elastic modulus and decreases of density contributed to increases in specific modulus and the highest specific modulus of 44.65 $GPa/g/cm^3$, which is about 70% higher than that of pure aluminum, is observed for Al-13%mg-4%Si. The highest specific strength of 204 $MPa/g/cm^3$ is obtained for the same alloy, which is equivalent to 7075-T6.

4. CONCLUSIONS

Structures and mechanical properties of rapidly solidified P/M materials of Al-Mg-Si ternary alloys with higher alloying additions than the commercial Al-Mg-Si alloys have been studied and compared to the I/M reference materials. Tensile strength of the as-extruded P/M materials is higher than that of the I/M counterparts. The tested alloys were grouped into two classes according to the changes of hardness and tensile strength of the P/M materials with increasing Mg+Si content. The alloys containing excess Mg to the Mg_2Si composition showed higher hardness and tensile strength than those without excess Mg at the same Mg+Si content. It is considered that both Mg solid solution and dispersion of Mg_2Si particles were contributing to the strength increases in the P/M materials. The highest tensile strength of 516 MPa at room temperature was obtained in the P/M material of Al-13%Mg-4%Si alloy.

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