EFFECT OF RAPID SOLIDIFICATION ON THE STRUCTURES AND MECHANICAL PROPERTIES OF Al-Si BASED CASTING ALLOYS

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ABSTRACT For the purpose of attaining property improvements of commercial aluminum casting alloys, rapidly solidified flakes were prepared by argon gas atomization and subsequent splat quenching onto a water-cooled copper roll. The flakes were consolidated to P/M materials by cold pressing, vacuum degassing and hot extrusion at a reduction of 25:1. Cast ingots of these alloys were also hot-extruded under the same conditions to the I/M reference materials. Both tensile strength and elongation of the as-extruded P/M materials are higher than those of the I/M counterparts. The highest increase of tensile strength was obtained in a hyper-eutectic Al-Si alloy (JIS AC9A). Increases in tensile strength due to rapid solidification are in correlation with the total amount of alloying elements forming second phase particles in the aluminum matrix. It is concluded that increases in strength of rapidly solidified P/M materials are obtained mainly by strengthening due to finer dispersoids.

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

1. INTRODUCTION

Improvements in strength at room and elevated temperatures, fracture toughness and resistance to stress corrosion cracking have been attained for various aluminum alloys by applying rapid solidification mainly due to refinement of metallographic structures [1-3]. However, most of the works were concerned to wrought alloys including alloys containing high amount of trasition metals and heat treatable high strength alloys. Little work has been reported on rapid solidification of casting alloys except for hyper-eutectic Al-Si alloys which are now in some practical use [4]. Since commercial casting alloys generally show superior fluidity in molten state, they are considered to be more suitable for rapid solidification by gas atomization and splat quenching. In this paper, with a purpose of attaining property improvement, 8 kinds of commercial aluminum casting alloys listed in JIS were rapidly solidified by argon gas atomization and subsequent splat quenching onto a water-cooled copper roll. All of the alloys studied are based on the Al-Si system of hypo-eutectic, eutectic and hyper-eutectic compositions. 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

Chemical compositions of the tested alloys are listed in Table 1. In the JIS alloy designation AC stands for casting alloys and ADC for die-casting alloys. They are all based on Al-Si alloys: 1 hyper-eutectic, 2 near eutectic and 5 hypo-eutectic compositions. They also contain Cu except for AC4C (ASTM 356.0). Rapid solidification was carried out by using an apparatus reported elsewhere [5]. Alloy melt which was held at a temperature 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 623K 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 753K for 25.2ks.

Metallographic structures were observed by OM and TEM for the RS flakes, P/M and I/M materials. Hardness changes of the P/M and I/M materials were measured after heating for 7.2ks at various temperatures. Vickers hardness was 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, 573 and 673K. The results are shown by the average of more than 3 tensile tests. The test piece was held at the test temperature for 300s.

Table 1: Chemical composition of tested alloys.

Alloy (JIS)	Composition (mass%)									Equivalent Alloy
	Si	Cu	Ni	Mg	Fe	Zn	Mn	Ti	Al	
AC2B	6.83	3.14	0.05	0.40	0.74	0.23	0.25	0.04	bal.	ASTM 319.0
AC4B	8.04	3.08	0.03	0.33	0.51	0.44	0.18	0.03	bal.	ASTM 333.0
AC4C	7.10	0.08	0.01	0.41	0.34	0.05	0.19	0.02	bal.	ASTM 356.0
AC8A	12.09	1.03	1.17	1.13	0.16	—	—	0.09	bal.	ASTM 336.0
AC8C	9.28	3.04	0.02	0.94	0.49	0.17	0.29	0.03	bal.	ASTM 332.0
AC9A	23.15	1.03	0.79	0.96	0.25	—	—	0.11	bal.	BS LM-29
ADC10	8.47	3.32	0.04	0.25	0.77	0.52	0.13	—	bal.	ASTM 380.0
ADC12	11.20	2.23	0.04	0.23	0.72	0.55	0.12	—	bal.	ASTM 383.0

3. RESULTS AND DISCUSSION

3.1 Structures and hardness of rapidly solidified flakes

These Al-Si based commercial casting alloys were easy to handle for gas atomization due to high fluidity of their melt. As shown in Fig. 1, TEM microstructures of rapidly solidified flakes of AC2B alloy (ASTM 319.0) reveals very fine dendritic cells of about 500nm. Microstructures of the rapidly solidified flakes are more or less the same for all the tested alloys. From the dendrite cell size, cooling rate during rapid solidification is estimated to be about 10^5 K/s [6].

Hardness changes of rapidly solidified flakes after annealing at various temperatures for 7.2

ks are shown in Fig. 2. In as rapidly solidified state, the highest hardness was obtained for a hyper-eutectic AC9A alloy, whereas the lowest for AC4C (ASTM 356.0). The flakes of all tested alloys showed some hardness increases after heating at 473K for 7.2ks. Supersaturated solid solution obtained in as rapidly solidified flakes decomposed to form precipitates, which caused hardening when heated at around 473K. Hardness of rapidly solidified flakes decreased when heated at above 573K for 7.2ks mainly because of structural coarsening.

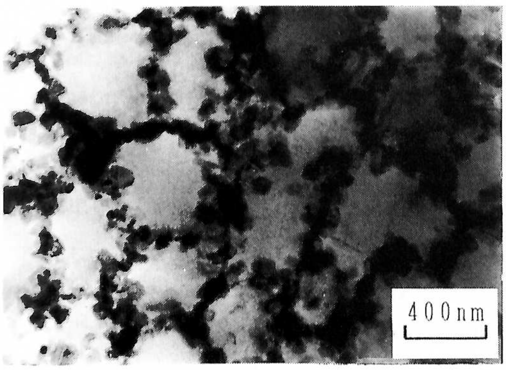


Fig. 1: TEM micrograph of as rapidly solidified flake of AC2B alloy.

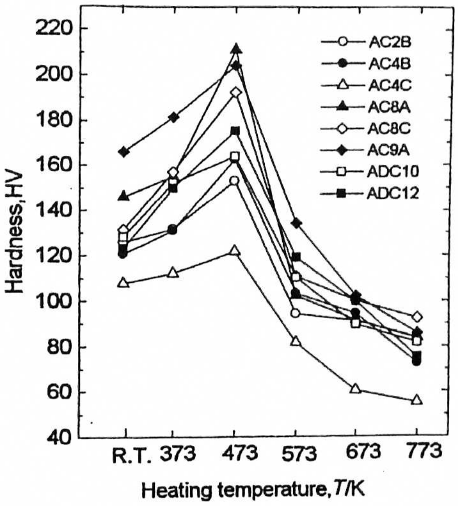


Fig. 2: Changes of hardness of rapidly solidified flakes after heating for 7.2 ks.

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

TEM micrographs of as-extruded P/M materials are shown in Fig. 3 in which fine second phase particles of submicron size are dispersed in the aluminum matrix. The dispersoids in AC8A (ASTM 336.0) alloy are observed to be finer and larger in quantity than in AC4C. Dispersed particles formed in the alloy with higher amount of alloying elements were observed to be finer and larger in quantity. The second phase particles observed in the rapidly solidified P/M materials are much finer than those in the I/M counterparts.

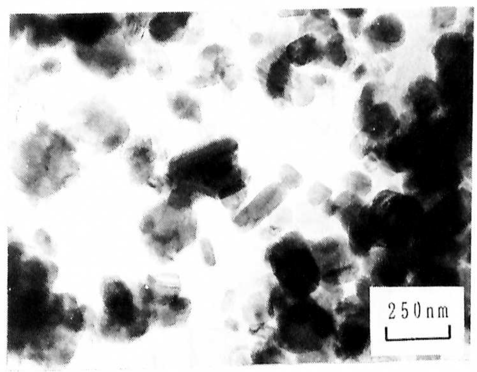
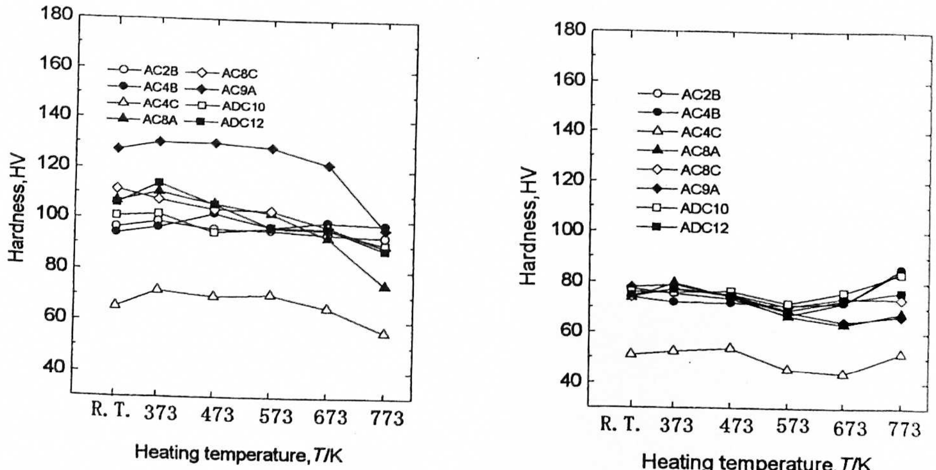


Fig. 3: TEM micrograph of as extruded P/M materials of AC8A alloy.

Changes of hardness of as-extruded P/M and I/M materials after heating at various temperatures for 7.2ks are shown in Fig. 4. Hardness of as-extruded P/M materials is higher than that of the I/M counterparts for all the alloys, thereby the effect of rapid solidification is clearly shown. However, hardness of as-extruded P/M materials is lower than that of the rapidly solidified flakes due to structural coarsening during vacuum degassing and hot extrusion. Hardness of hyper-eutectic AC9A alloy is highest for the P/M



(a) P/M materials (b) I/M materials

Fig. 4: Changes of hardness of as extruded P/M and I/M materials after heating for 7.2 ks.

material whereas it is not so for the I/M material. Hardness of AC4C alloy, which contains the least amount of alloying additions, is lowest for both P/M and I/M materials. Hardness of P/M materials is relatively unchanged after heating at up to 673K, the hot-extrusion temperature of these materials. However, it drops after heating at 773K due to structural coarsening whereas the I/M materials shows no hardness drop even after heating at 773K.

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

Tensile strength at room temperature of as-extruded P/M and I/M materials are shown in Fig. 5. Tensile strength of P/M materials is higher than that of the I/M counterparts, thereby rapid solidification is effective in increasing strength of these Al-Si based alloys. Particularly, the highest increase in tensile strength is attained for a hyper-eutectic AC9A alloy. Tensile strength of the rapidly solidified P/M material of AC9A is 400 MPa, whereas that of the I/M material is below

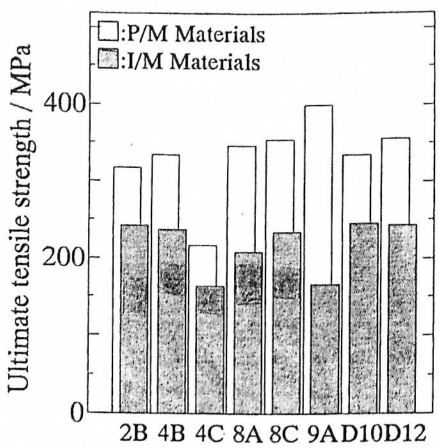


Fig. 5: Tensile strength of as extruded P/M and I/M materials.

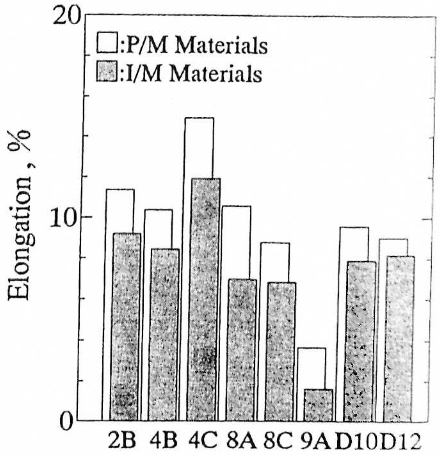


Fig. 6: Elongation of as extruded P/M and I/M materials.

200 MPa. Low strength of the I/M AC9A is attributed to coarse primary Si formed during ingot casting, resulting in low ductility of the as-extruded I/M material. On the other hand, primary Si crystals formed by rapid solidification are much finer. The lowest increase in strength by rapid solidification is observed in a hypo-eutectic AC4C alloy; tensile strength of its P/M material is 217 MPa which is lowest of the rapidly solidified P/M materials.

Fig. 6 shows tensile elongation at room temperature of as-extruded P/M and I/M materials. Higher elongation is observed for the rapidly solidified P/M materials than the I/M counterparts in all the tested alloys. The higher ductility of rapidly solidified P/M materials is attained by finer dispersion of the second phase particles. Highest elongation was obtained for the P/M material of AC4C whereas the lowest for the I/M material of hyper-eutectic AC9A. The low ductility of AC9A is due to formation of primary Si crystals.

Increases in tensile strength by rapid solidification is plotted against the total amount of alloying additions of each alloy, that is, Si+Cu+Ni+Mg mass % in Fig. 7, in which a good linear correlation is observed. The increase of strength is about 50 MPa in AC4C which contains lowest amount of the alloying additions among the tested alloys. The highest increase of above 200 MPa in strength is obtained in AC9A which contains highest amount of alloying additions. Alloying elements such as Si, Cu and Ni have low solid solubility in Al at temperatures below the hot extrusion temperature of 673K. Solid solubility of Mg in Al is high but it decreases rapidly with simultaneous additions of Si or Cu. Hence, the

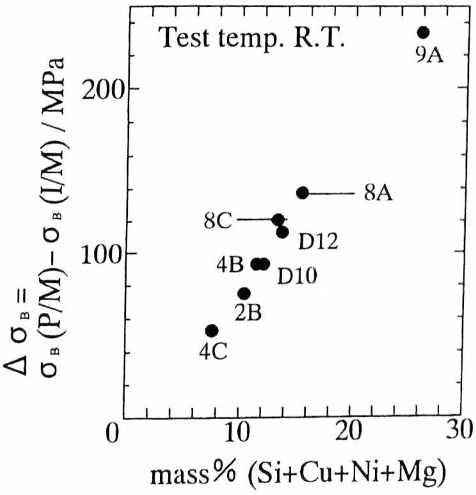
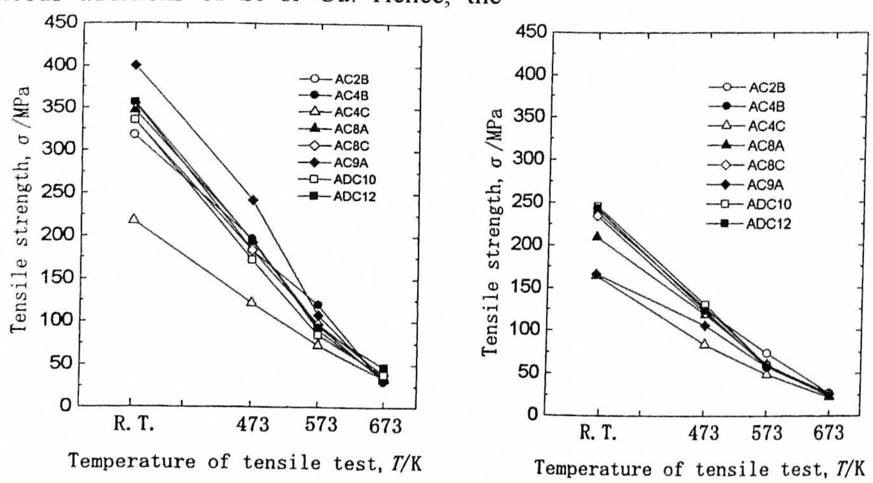


Fig. 7: Increases in tensile strength obtained by rapid solidification vs. Si+Cu+Ni+Mg content.



(a) P/M materials (b) I/M materials

Fig. 8: Tensile strength of as extruded P/M and I/M materials at various temperatures.

amount of Si+Cu+Ni+Mg is proportional to the amount of second phase particles formed in the as-extruded materials of these tested alloys. Increases in strength obtained by rapid solidification are mainly attained by dispersion strengthening by finer second phase particles formed in the rapidly solidified P/M materials.

Tensile strength of P/M and I/M materials at various temperatures is shown in Fig. 8. At all temperatures, tensile strength of the P/M materials is higher than that of the I/M counterparts thereby showing that rapid solidification is still effective in strengthening these materials at elevated temperatures. Tensile strength decreased with rising temperature for both materials. At 673K, tensile strength of all the P/M materials approaches to 40 MPa and that of the I/M materials to 25 MPa.

Tensile elongation increased with rising test temperature for both P/M and I/M materials. At 673K, both P/M and I/M materials of these casting alloys are very ductile showing elongation as high as 50%. Except a hyper-eutectic AC9A alloy, ductility of P/M materials at elevated temperatures is nearly same as that of I/M counterparts. Ductility of the AC9A P/M material is much higher than that of the I/M material at all test temperatures. As mentioned before, this is attributed to coarse primary Si crystals formed in the I/M material.

4. CONCLUSIONS

Property improvements of commercial Al-Si based casting alloys have been attained by applying rapid solidification and P/M method. Both tensile strength and elongation of the as-extruded P/M materials are higher than those of the I/M counterparts. The highest increase of tensile strength was obtained in a hyper-eutectic Al-Si alloy (JIS AC9A). Increases in tensile strength due to rapid solidification are in correlation with the total amount of alloying elements forming second phase particles in the aluminum matrix. It is concluded that increases in strength of rapidly solidified P/M materials are obtained mainly by strengthening due to finer dispersoids.

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