

S. SAIKAWA<sup>\*,‡</sup>, G. AOSHIMA<sup>\*\*</sup>, S. IKENO<sup>\*\*\*</sup>, K. MORITA<sup>\*\*\*\*</sup>, N. SUNAYAMA<sup>\*\*\*\*</sup>, K. KOMAI<sup>\*\*\*\*</sup>

## MICROSTRUCTURE AND MECHANICAL PROPERTIES OF AN Al-Zn-Mg-Cu ALLOY PRODUCED BY GRAVITY CASTING PROCESS

## MIKROSTRUKTURA I WŁAŚCIWOŚCI MECHANICZNE STOPU Al-Zn-Mg-Cu WYTWORZONEGO METODĄ ODLEWANIA GRAWITACYJNEGO

High-strength aluminum alloy are widely used for structural components in aerospace, transportation and racing car applications. The objective of this study is to enhance the strength of the Al-Zn-Mg-Cu alloy used for gravity casting process. All alloys cast into stepped- form sand mold (Sand-mold Casting; SC) and Y-block shaped metal mold(Permanent mold Casting; PC) and then two –step aged at 398 -423 K after solution treated at 743 K for 36 ks. The tensile strength and total elongation of the two-step aged SC alloys were 353-387 MPa and about 0.4% respectively. This low tensile properties of the SC alloys might be caused by remaining of undissolved crystallized phase such as Al<sub>2</sub>CuM, MgZn<sub>2</sub> and Al-Fe-Cu system compounds. However, good tensile properties were obtained from PC alloys, tensile strength and 0.2% proof stress and elongation were 503-537 MPa , 474-519 MPa and 1.3-3.3%.

The reason of the good properties in PM alloys, is the lowed amount of undissolved crystallized phase than that of SC ones and primary crystallized alpha-Al phase was finer due to high cooling rate at solidification in casting.

*Keywords:* Al-Zn-Mg-Cu Alloy, Casting, Microstructure, Mechanical Property

Stopy glinu o wysokiej wytrzymałości są szeroko stosowane jako elementy konstrukcyjne w lotnictwie, w transporcie oraz w samochodach wyścigowych. Celem badań prezentowanych w niniejszej pracy jest zwiększenie wytrzymałości stopu Al-Zn-Mg-Cu przy zastosowaniu metody odlewania grawitacyjnego. Stopy odlewano w formie piaskowej (ang. Sand-mold Casting; SC) oraz w formie metalowej w kształcie Y (ang. Permanent mold Casting; PC), a następnie poddawano dwustopniowemu starzeniu w zakresie temperatur 398-423 K po przesycaaniu w 743 K w czasie 36 ks. Wytrzymałość na rozciąganie stopów SC po dwustopniowym starzeniu wyniosła 353-387 MPa, natomiast całkowite wydłużenie – ok. 0,4%. Niska wytrzymałość stopów SC na rozciąganie może być spowodowana pozostałościami faz krystalicznych, tj. związków Al<sub>2</sub>CuM, MgZn<sub>2</sub> i Al-Fe-Cu. Natomiast stopy PC charakteryzowały się dobrymi właściwościami mechanicznymi. Wytrzymałość na rozciąganie, umowna granica plastyczności R<sub>0,2</sub>, plastyczność oraz wydłużenie wyniosły odpowiednio 503-537MPa, 474-519MPa oraz 1,3-3,3%. Lepsze właściwości mechaniczne stopów PC można wytłumaczyć mniejszą ilością nierozpuszczonych faz krystalicznych w porównaniu ze stopami SC oraz mniejszą grubością głównej fazy krystalicznej alfa-Al wynikającej z wysokiej szybkości chłodzenia do punktu krzepnięcia przy odlewaniu.

### 1. Introduction

In the aerospace, racing car and motorcycle race fields, high-strength aluminum alloys are widely used for body, structural, and engine components, where weight reduction is needed to improve movement performance and fuel efficiency. The history of the development of high-strength aluminum alloys is old and begins with discovery of the Al-Cu-Mg system alloys, i.e. Duralumin, approximately one century and follows now [1,2]. Then Zinc was added to Al-Zn-Mg-Cu alloys, called Extra Super Duralumin (ESD). It was developed in the 1936 in Japan and was stronger than Duralumin. It was used for components in more critical aerospace and lighter applica-

tions filed and so on. Until recent years, the research and development efforts have been intense mainly in the field of wrought products, for example, extrusion, rolling, forging and stamping, because it can be strengthened by not only heat treatment but also work- hardening [1,2].

On the other hand, cast products also have some advantages over the wrought products, because of the components with complicated form can be cast to near net shape in one run.

Therefore, concentrated development and study of the cast alloys applied for sand and metal (permanent) casting process, which began in the 1960s, up to recent years [3]. However, since the Al-Zn-Mg-Cu alloys are hard to cast in the gravity

\* GRADUATE SCHOOL OF SCIENCE AND ENGINEERING FOR RESEARCH, UNIVERSITY OF TOYAMA (UNIVERSITY, TOYAMA-SHI, JAPAN)

\*\* GRADUATE SCHOOL OF SCIENCE AND ENGINEERING FOR EDUCATION, UNIVERSITY OF TOYAMA (UNIVERSITY, TOYAMA-SHI, JAPAN)

\*\*\* HOKURIKU POLYTECHNIC COLLEGE (UNIVERSITY, UOZU-SHI, JAPAN)

\*\*\*\* TANIDA LTD (COMPANY, KANAZAWA-SHI, JAPAN)

‡ Corresponding author: saikawa@eng.u-toyama.ac.jp

casting, there has been limited and a few research on this alloys.

In this study, we investigated the relationship between the microstructure and mechanical properties in Al-5-8Zn-2.3Mg-1.8Cu (wt%) system alloys cast by sand and metal mold process that was found of the best Al-Zn-Mg-Cu casting alloy in our previous study [4].

**2. Experimental procedures**

The target and analysis compositions of the investigated alloys are listed in Table 1. The starting materials were pure Al (99.7%), pure Zn (99.999%), pure Cu (99.9999%), Al-10%Mg and Al-5%Ti-1%B master alloys. Then the chopped materials melted in a large gas furnace (250 kg max) for sand mold casting and in a small electrical resistance furnace (5 kg max) for metal mold casting in order to prepare alloys with different amount of Zn. The temperature for melting was kept at 993-1013 K. The Deoxidation was conducted by flux containing salts, which mixed into molten metal and slag removal. To remove dissolved hydrogen from molten metal argon was purged into metal through carbon tube for 3-10 minutes. Flow rate of argon gas was 1-5 L/min. Two kinds of the castings were cast by using two molds, one was a Y-block shaped metal mold, and the other was a stepped sand mold castings shown in Fig. 1. Pouring temperature into molds were about 973-1013 K. Before casting, the metal mold and sand mold was pre-heated up to 453-473 K and 323 K. After casting,

microstructures were examined using an optical microscope (OM) and aJEOL 6700F field emission scanning electron microscope (FE-SEM) equipped with an energy dispersive X-ray system (EDS). The crystallized phases identification was also performed by X-ray diffraction method (XRD; Bruker AXS, D8 Discover).

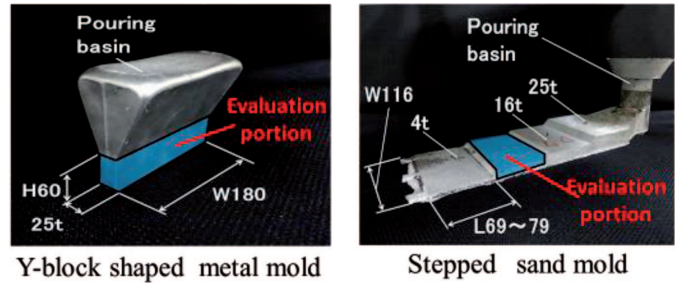


Fig. 1. Appearance of the castings used in this study

**3. Result and discussion**

The results of OM observation for the as-cast alloy are shown in Fig. 2 and 3. There is no remarkable difference in macro structure of all castings using the OM observation at low magnification in Fig. 2. The macro structures mainly consist of the primary crystallized alpha-Al phase (white region), secondly crystallized eutectic region (dark gray region). It is typical macro structure in eutectic type aluminum alloy produced by general casting method.

TABLE 1  
Metallic radii of rare earth metals and magnesium [12]

Alloy Code	Zn	Mg	Cu	Ti	B	Al	Mold
5Zn-M	5	2.30	1.80	0.09	0.018	bal.	Metal (Permanent)
	4.83	2.69	1.88	0.13	0.026	bal.	
6.5Zn-M	6.5	2.30	1.80	0.09	0.018	bal.	Metal (Permanent)
	5.93	2.69	1.92	0.13	0.026	bal.	
8Zn-M	8	2.30	1.80	0.09	0.018	bal.	Metal (Permanent)
	7.38	2.86	2.06	0.13	0.026	bal.	
5Zn-S	5	2.30	1.80	0.08	0.016	bal.	Sand
	4.79	2.35	1.54	0.10	0.020	bal.	
8Zn-S	8	2.30	1.80	0.08	0.016	bal.	Sand
	7.67	2.45	1.85	0.10	0.020	bal.	

Upper row: Target compo., Lower row; Analysis compo.

evaluation samples were cut off from the two kind of castings and were solution treated at 743 K for 36 ks and then quenched into water. These samples were naturally aged at 3.6-86.4 ks and then were artificially aged. Two step aging cycle was employed, 398 K for 36 ks followed by 423 K for 14.4 ks. Tensile testing was carried out for the heat-treated test pieces at room temperature, using Instoron type testing machine working at a cross-head speed of 2 mm/60s. Thin samples cut from evaluation portion of the castings were polished and then etched by Keller's reagent to reveal the microstructures. These

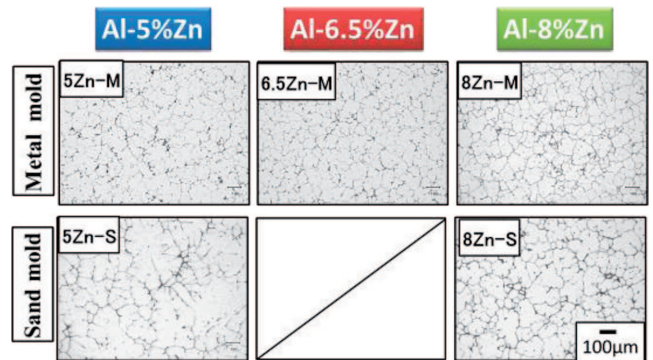


Fig. 2. Optical micrographs of the as-cast microstructure with a low magnification

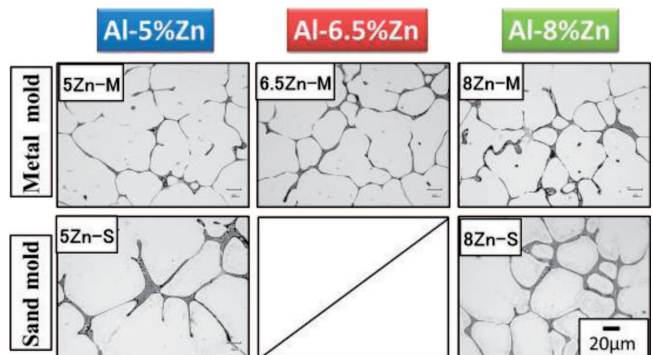


Fig. 3. Optical micrographs of the as-cast microstructure with a high magnification

For the purpose of identification relatively fine phases, except the primary alpha-Al phase revealed in Fig. 3, the microstructure was observed at high magnification by OM. The primary crystallized alpha-Al grain size of metal mold castings (5Zn-M, 6.5Zn-M and 8Zn-M) are finer than that of the sand mold castings (5Zn-S and 8Zn-S). The secondary crystallized phase (dark gray) located around the alpha-cells and its gaps increase with increasing the zinc content.

Fig. 4 shows X-ray diffraction pattern of the as-cast 5Zn-M, 6.5Zn-M and 8Zn-M alloy castings. The alpha-Al phase and eta-MgZn<sub>2</sub> phase were detected in all alloy castings. Also, a relatively low Zn S-Al<sub>2</sub>CuMg phase was detected in 5Zn-M and 6.5Zn-M alloy castings.

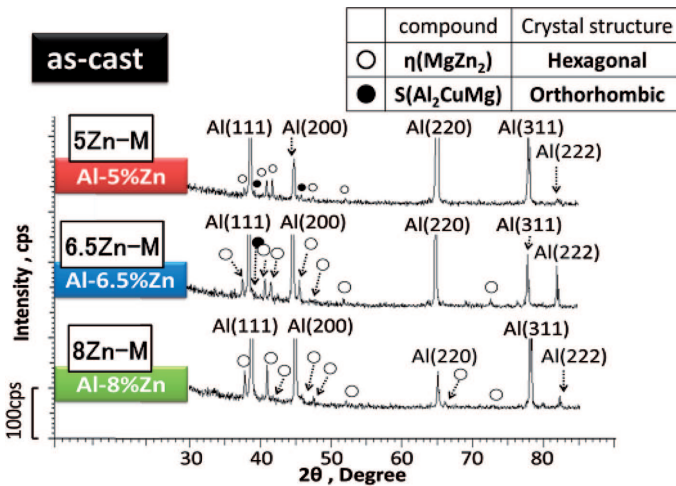


Fig. 4. X-ray diffraction pattern of the as-cast

Fig. 5 shows the results of the chemical analysis for intermetallic compounds in the as-cast 6.5Zn-M alloy. The EDX point analyses with FE-SEM were carried out in areas 1, 2 and 3 and, according to the identification based on our previous study [2,4], these were distinguished to four kinds. The portion-1 is the alpha-Al phase, portion-2 consists of eta-MgZn<sub>2</sub> and S-Al<sub>2</sub>CuMg phases, portion-3 is an Al-Fe-Cu system compound. The results of other alloy castings are very similar to 6.5Zn-M alloy castings.

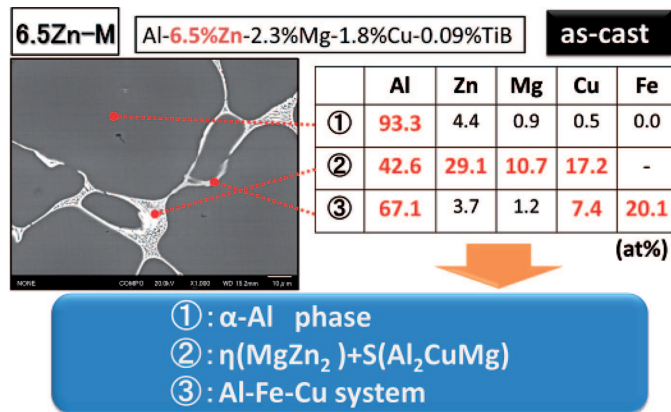


Fig. 5. Result of the analysis for intermetallic component in as cast of 6.5Zn-M alloy (Al-6.5%Zn-2.3Mg-1.8Cu-0.09TiB)

Fig. 6 shows the results of tensile test in Al-Zn-Mg-Cu alloys after 2-step artificial aging. The superior characteristic is obtained in the 6.5Zn-M alloy cast into a metal mold

and 2-stepped-aged condition. The U.T.S. and 0.2%P.S. and elongation are 537MPa, 519MPa and 1.3%. The comparison of U.T.S. and elongations values revealed that the change the casting process from sand to metal mold casting is the most effective procedure to enhance tensile properties of the casting.

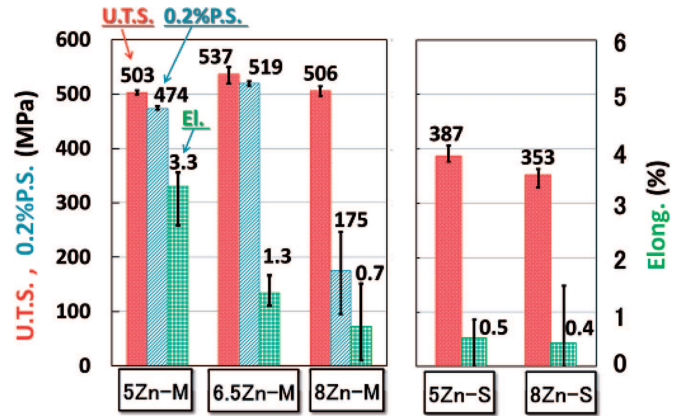


Fig. 6. Results of tensile test for Al-Zn-Mg-Cu system alloy

Fig. 7 shows the OM micrographs of the solutionizing and 2-step aged state. The amount of secondary crystallized phases around alpha-Al phase, i.e. eta-MgZn<sub>2</sub> and S-Al<sub>2</sub>CuMg are decreased comparing with the as-cast state in Fig. 3. It was due to be solid-solution in the matrix. However, the undissolved phases remained on grain boundaries and cell gaps. The amount of those phases increased in the sand mold castings (5Zn-S and 8Zn-S).

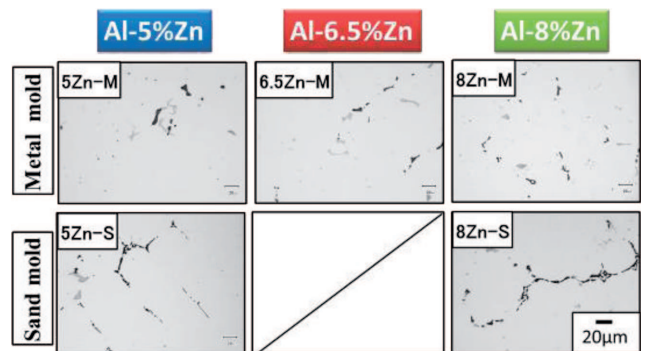


Fig. 7. Optical micrographs of the solutionizing and 2-step aging microstructures

Fig. 8 shows the results of the analysis for remained phases in solutionizing and 2-step aged 6.5Zn-M alloy castings. EDX point analysis with FE-SEM are carried out in areas 1, 2 and 3.

The results are similar to that in Fig. 5. These remained phases were mainly eta-MgZn<sub>2</sub>, S-Al<sub>2</sub>CuMg phase and Al-Fe-Cu system compounds.

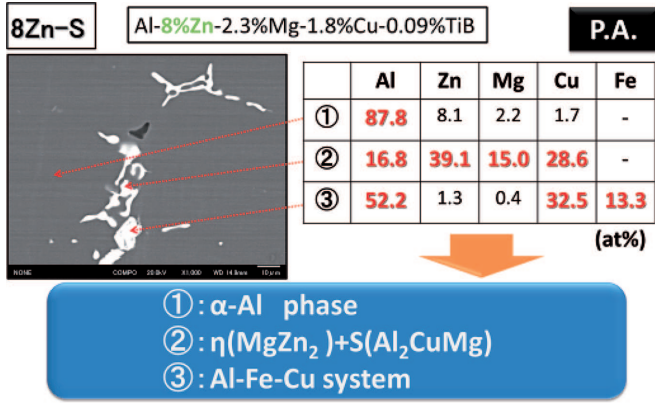


Fig. 8. Result of the analysis for intermetallic component in two step aged of 8Zn-S alloy (Al-8%Zn-2.3Mg-1.8Cu-0.09TiB)

Fig. 9 shows the Optical micrographs of cross-sections under fractured surfaces after tensile test. Observation results of the 5Zn-S and 8Zn-S alloy castings with lowered tensile test values, there are a lot of those phases are remained on the fractured surfaces.

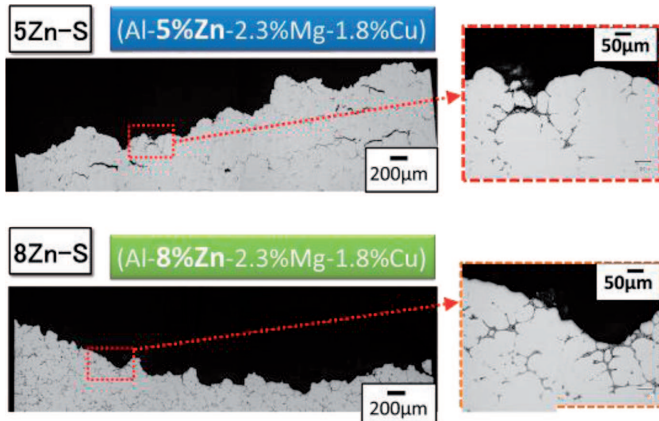


Fig. 9. Optical micrographs of cross-sections under fractured surfaces after tensile test

Therefore, the main reason for the improvement in metal mold castings (5Zn-M, 6.5Zn-M and 8Zn-M) is high probably due to the reduce of alpha-Al grain size of the casting, leading

to a finer distribution of secondary phases [5]. The remained phases such as the eta-MgZn<sub>2</sub>, S-Al<sub>2</sub>CuMg and Al-Fe-Cu system compounds are brittle and are considered as important crack initiating sites during loading in tensile test.

#### 4. Conclusions

The relationship between the microstructure and mechanical properties in Al-5-8Zn-2.3Mg-1.8Cu (wt%) system alloys cast by sand and metal mold process are studied. The following conclusions can be drawn from this study.

1. The microstructure in Al-5-8Zn-2.3Mg-1.8Cu (wt%) system alloys cast by sand and metal mold process consists of alpha-Al, eta-MgZn<sub>2</sub>, S-Al<sub>2</sub>CuMg phases and Al-Fe-Cu system compounds.
2. The results of tensile test in Al-6.5Zn-2.3Mg-1.8Cu (wt%) system alloys after 2-step artificial aging. The superior characteristic is obtained in the 6.5Zn-M alloy(Al-6.5Zn-2.3Mg-%Cu (wt%) system) cast into a metal mold and 2-stepped-aged conditon. The U.T.S., 0.2%P.S. and elongation were 537 MPa, 519 MPa and 1.3%. The comparison of U.T.S. and elongation values revealed that the change the casting process from sand to metal mold casting is the most effective procedure to enhance tensile properties of the casting.
3. The main reason for the improvement of mechanical properties in metal mold castings (5Zn-M, 6.5Zn-M and 8Zn-M) is likely due to the reduce alpha-Al grain size of the casting, leading to a finer distribution of secondary phases.

#### REFERENCES

[1] M. Hirano, J.of JILM **18**, 447-484 (1991).  
 [2] Y. Baba, J of JILM **39**, 378-395 (1989).  
 [3] T. Takahashi, J of JILM **41**, 228-244 (1968).  
 [4] T. Furuta, G. Aoshima, S. Saikawa, K. Terayama, S. Ikeno, K. Fujii, K. Komai, Reports of the JFS Meeting **163**, 35 (2013).  
 [5] T. Kobayashi, Mater Sci Eng. A, 8-16 (2000).