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Characteristics and microstructure of newly designed Al–Zn-based alloys for the die-casting process

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ABSTRACT

Al–Zn-based alloys with high strength of >470 MPa for die-casting were successfully fabricated without melt modification and post-casting heat treatment. We designed Al-based alloys containing more than 20 wt% of Zn for the die-casting process. The matrix phase of the alloy was angular α-Al surrounded by a very fine lamellar structure of α-Al and η-Zn. The average grain size of the matrix was relatively small (~25 μm), and a complex network of eutectoid α + η, supersaturated η, β, and Cu-related intermetallic particles formed at the grain boundaries or non-equilibrium solidification phases. This microstructural feature obtained by the addition of more than 20 wt% Zn significantly enhanced the strength of the Al–Zn-based alloys. Furthermore, we investigated the fluidity and wear properties of the developed alloys, which improved as the Zn content was increased.

1. Introduction

Al–Si alloys with high specific strength, low density, and good castability are widely used as die-casting materials for automobile and aerospace components [1–3]. Because they have some microstructural problems induced by the formation of a flake-type brittle Si phase during solidification, modification to a fine and fibrous eutectic Si structure is essential for the casting process [4]. Furthermore, T6 heat treatment must be added to the die-casting process during manufacturing to attain high strength of <320 MPa [5,6]. However, these additional processes increase production costs and reduce productivity in the Al casting industry. The most effective method to solving these problems is to find alloy systems that are applicable to the die-casting process and provide high strength in the as-cast state.

Zn-added Al-based alloys represented by the 7XXXseries Al alloys, and they extensively used in aircraft construction and other high-strength applications [7]. The 7XXX series Al alloys contain 4–7% Zn, and their high strength achieved by fine-scale precipitation of metastable Zn- and Mg-rich phases during age-hardening heat treatment [8]. Although they have high strength of up to 400 MPa, 7XXX series Al alloys cannot be applied to the die-casting process owing to their low castability. Meanwhile, die-cast Al-added Zn-based alloys such as ZA27 have many merits such as good castability, high strength with good elongation, and excellent wear resistance [9]. However, the dimensional instability of Cu-added (>3%) Zn-based alloys caused by decomposition of the ε phase ($CuZn_4$) limits their application [10].

Recently, Alemdağ et al. found that the Al–40Zn–3Cu alloy fabricated by gravity casting showed good wear resistance and superior mechanical properties such as a tensile strength of 370 MPa and elongation of 5%, and they suggested using the alloy as a wear-resistant material [11–13]. The melting temperature of Al–Zn alloys containing more than 20 wt% Zn is much lower than that of generally used die-cast Al alloys, and their solidification ranges in the Al–Zn alloy phase diagram are wide enough to achieve well-defined casting properties [14]. In economic terms, Al alloys with high Zn content also yield several cost benefits such as extension of die life, cycle-time reduction, and energy savings for the melting process. Furthermore, the developed alloys show improved mechanical properties with the addition of a large amount of Zn, which also lead to the presence of the α + η phase or η-rich phase at the grain boundary or non-equilibrium solidification region due to the monotectic reaction ($L_1 = \alpha + L_2$) [15].

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Consequently, α-Al is enclosed with the Zn-rich phase to form a network structure; Cu is added to improve the strength of the alloy [16], and the resulting intermetallic compound is employed or located at the η-rich-phase grain boundary or non-equilibrium solidification region. Owing to such solidification characteristics, Al–Zn-based alloys can exhibit very high strength. Previous reports and the binary phase diagram of Al–Zn alloys suggest that Al–Zn-based alloys can be used in the die-casting process to fabricate high-strength casting products.

In this study, we attempted to use Al-based alloys containing more than 20 wt% Zn in the die-casting process. In order to design new die-cast alloys with high mechanical properties, Al-based alloys with various Zn content prepared by die-casting, and their microstructure and mechanical properties analyzed. We evaluated the flow length of the developed Al–Zn-based alloys, which enhanced by increasing the amount of added Zn. Moreover, the developed alloys had lower melting points, which assumed to improve the lifetime of the die-casting mold. In addition, the developed alloys were determined to have excellent wear characteristics owing to the high fraction of non-equilibrium solidification phases or Zn-rich phases. Therefore, we investigated their applicability as a class of structural material by observing various characteristics of the die-cast Al–Zn-based alloys.

2. Experimental procedure

Using high-purity Al, Zn, and Cu ingots, a series of Al–Zn-based alloy ingots containing 20–45 wt% of Zn and 2.5 wt% of Cu was prepared in an electric-resistance furnace. In addition, 0.3 wt% of Fe and 0.4 wt% of Si were added to prevent metallic mold burning [17] and improve castability [18]. Table 1 shows the chemical composition of the prepared ingots analyzed by inductively coupled plasma–atomic emission spectroscopy (ICP-AES, SP51550, Seiko).

The prepared ingots re-melted at 670 °C and casting experiments carried out using a die-casting machine (650 tonnages, Toyo). The casting conditions summarized in Table 2. For each composition, 20 tensile test bars prepared by die-casting, and their tensile properties were measured using an Instron-5989 tensile test machine with a crosshead speed of 1 mm/min, which is equivalent to a strain rate of $2.78 \times 10^{-4}\ s^{-1}$. The hardness of the Al–20–45Zn-based die-casting alloys was determined using a Vickers hardness tester (HM-122, Akashi, Japan) with a diamond indenter at a load of 50 gf. In addition, the microvickers hardness of each phase (α-Al phase, α + η phases and Θ phases) for the Al–45Zn-based alloys were measured by using a cross-section of the tensile testing sample (810–219 K, Mitutoyo, Japan, load-0.01 g).

The α-phase particle size and the volume fraction of the non-equilibrium solidification phase were determined by electron backscattering diffraction (EBSD; S-4300, Hitachi) at a scanning step size of 0.7 μm. The EBSD data were processed using orientation imaging microscopy analysis software (TSL-OIM, EDAX); the data points with a confidence index below 0.1 were removed from the EBSD data. The structural identification and microstructural examination were performed using X-ray diffractometry (XRD; Cu K_α, Rigaku).

The microstructure of the samples was examined by a field-emission scanning electron microscope (FE-SEM; Supra40, Carl Zeiss) equipped with an energy-dispersive spectrometer (EDS). A 3% hydrofluoric acid (HF) solution was used as an etchant. The size and morphology of the α phase were determined by image analysis (Image-Pro Plus, Media Cybernetics). The thermal properties, such as the melting temperature and phase-transformation temperature, liquidus temperature, solidus temperature, and the latent heat of the developed Al–Zn alloys and ADC12 alloy were measured repeatedly by differential scanning calorimetry (DSC; DSC 8270, Rigaku), during which the samples were examined at a heating rate of 20 °C/min. The fluidity of the developed alloys evaluated by using a spiral mold, shown in Fig. 1, which was pre-heated to ~200 °C.

Table 1
Chemical composition of the high pressure die cast Al–Zn-based alloys as determined by ICP-AES, (wt%).

Alloy	Zn	Cu	Si	Fe	Al
(a)	19.704	2.416	0.584	0.315	Balance
(b)	28.597	2.371	0.539	0.383	Balance
(c)	38.942	2.465	0.543	0.278	Balance
(d)	43.861	2.507	0.531	0.294	Balance

The fluidity of the developed Al–20–45Zn-based die-casting alloys and ADC12 alloy evaluated by using a spiral mold, shown in Fig. 1. The mold was made of SKD 61 hot working steel. The produced flow channel size was the thickness 4 mm, width 11 mm and length 2000 mm. The mold release agent (BN, Bron-Ntride) sprayed to the entire mold and then completely dried at 200 °C heating furnace. After pouring the 1.2 kg molten metal (same weight for all alloys) of 720 °C to Basin (Fig. 1(b)), which is molten metal temperature of 680 °C (same pouring temperature for all sample), we removed injection rods (pouring bar, Fig. 1(a)), in order to uniformly pour the molten metal to flow channel in the fluidity test spiral mold pre-heated at 200 °C.

Wear tests performed using a conforming ball-on-disc test machine (Plint TE 770, Phoenix Tribology Ltd.). The samples (Φ25 mm × 10 mm) were prepared from the cross section of the runner parts in the developed Al–20–45Zn-based die-casting alloy samples, and the surface of each of the wear-test specimens had a roughness of 0.02 μm following the test. The material of the reciprocating specimen to the developed Al–Zn-based alloy was STB-2 bearing steel. The friction coefficient with wear depth and width as a function of Zn content in the Al–Zn-based alloys were measured at a distance of about 300 m, a load of 1 N, and a rotational speed of 70 rpm. The wear depth and width of the sample measured by using MG-V135 (Samyang, Korea) analysis equipment. The worn surfaces of the wear samples were examined using SEM.

3. Results and discussion

3.1. Microstructure of developed Al–Zn-based alloys

Fig. 2(a)–(d) display the change in microstructure of the Al–Zn-based alloys prepared via high-pressure die casting as a function of the Zn content; these images reveal an essential evolution in morphology and size of the α-Al phase. The bright regions in the images correspond to the Al-rich (α) phase, while the gray regions correspond to the grain boundary regions consisting of the Zn-rich (η) and non-equilibrium α + η phases. The increase of Zn content changed the grain morphology from dendrite type to granular type. This granular morphology shown in Fig. 2(c) and (d) was similar to the Al alloys fabricated by semi-solid process. In addition, the grain size of α-Al phase with increasing Zn content as shown in Fig. 2(a)–(d). The EBSD micrographs in Fig. 2(e)–(h) clearly show this microstructural change. From the analysis results of EBSD micrographs, the average α-Al grain size significantly decreased from 45 μm to 25 μm with increasing Zn content from 20% to 45%. As shown in Fig. 2, the volume fraction of non-equilibrium α + η grain boundary regions increased from 9% to 28% with increasing Zn content, which may easily explained by the lever rule in the Al–Zn phase diagram [14]. The reduction of α-Al phase volume fraction can be one of the reasons for the small grain size of Al–Zn alloys with large amount of Zn content. Another important factor for the grain refinement of Al–Zn alloys in the present study is the melt superheat induced by the decrease solidus and the enlarged mushy