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Short communication

Insight into the partial solutionisation of a high pressure die-cast Al-Mg-Zn-Si alloy for mechanical property enhancement

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ABSTRACT

A partial solution treatment was investigated to enhance the mechanical properties for a die-cast Al-Mg-Zn-Si alloy. The strengthening mechanism was identified that the $Mg_{32}(Al, Zn)_{49}$ intermetallics and equilibrium η-$MgZn_2$ phase formed in the as-cast microstructure were partially dissolved into the α-Al matrix during solutionising and the fine semi-coherent η'-$MgZn_2$ phase was precipitated during subsequent aging. Consequently, the unique microstructure was characterised by the co-existence of equilibrium η-$MgZn_2$ phase and metastable η'-$MgZn_2$ phase in the α-Al matrix, together with the un-changed Mg_2Si eutectic and remnant $Mg_{32}(Al, Zn)_{49}$ intermetallics in the Al-Mg-Zn-Si alloy.

1. Introduction

The application of thin-wall components made by high pressure die-casting of aluminium alloys is one of the favourable options to make light weight structures in transport industry [1,2]. However, the existing die-cast aluminium alloys based on Al-Si, Al-Si-Cu and Al-Mg-Si systems are generally not desirable to provide required mechanical properties, in particular, the yield strength and elongation under as-cast condition [3]. This has been partially attributed to the presence of substantial amount of porosity in die-castings, which results in the inapplicable of standard full solution and ageing treatment to enhance the mechanical properties [4,5]. In order to solve the related problems, a quick solution treatment process was developed specially for die-cast Al-Si-Cu alloys to eliminate the formation of blisters and porosity in the heat-treated components [6,7] which has been confirmed to be able to improve the mechanical properties of die cast alloys [8,9].

Recently, a die-cast Al-Mg-Zn-Si alloy was developed by forming specific intermetallics ($Mg_{32}(Al, Zn)_{49}$, Mg_2Si and $MgZn_2$) under as-cast condition [10]. The alloy has been successfully used to make high pressure die castings to replace the CNC machined aluminium components in aerospace-industry [11]. One of the significant advantages was that the alloy was designed for precipitation strengthening through solutionising and ageing. However, when a solutionising process at 490–510 °C for 30–60 min was applied, the Al-Mg-Zn-Si alloy was prone to forming blisters or overfiring because the equilibrium reaction of Al-$MgZn_2$ eutectic was about 470 °C [4]. Therefore, it is essential to investigate a new heat treatment for the Al-Mg-Zn-Si alloy to improve simultaneously the yield strength and elongation without forming blisters in the castings. In this paper, the study was focused on the strengthening mechanism of the Al-Mg-Zn-Si alloy after being partially solutionised and subsequently aged. The microstructure and mechanical properties of the alloy were reported and discussed.

2. Experimental

A standard process of melting, degassing, casting and trimming was used to prepare the Al-10.2Mg-3.2Zn-2.7Si (wt%) alloy. The standard casting samples were made by a 4500 kN high pressure die casting machine. The alloy composition was obtained by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) using the specimen directly cut from casting body. The partial solution was performed in a ventilated oven at 430 ± 0.5 °C for different times. The subsequent ageing was performed at 160 ± 0.5 °C for 90 min.

The tensile tests were conducted following ASTM standard B557, using an Instron 5500 Universal Electromechanical Testing System equipped with Bluehill control software and a ± 50 kN load cell. The gauge length of the extensometer was 25 mm and the ramp rate for extension was 2 mm/min. Each set of data reported tensile properties

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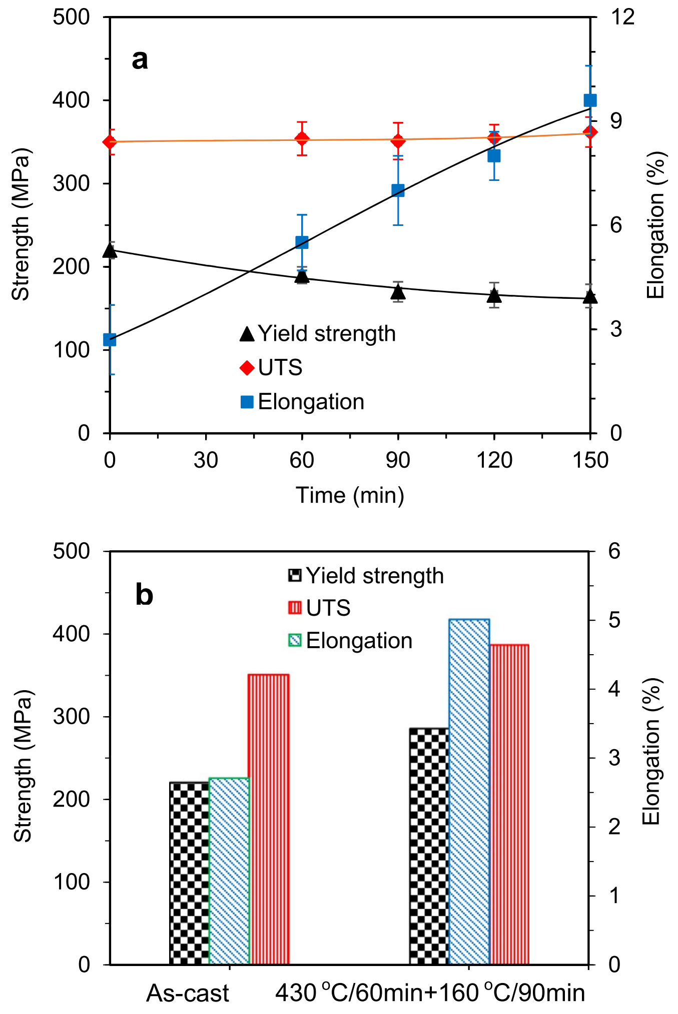

Fig. 1. Mechanical properties of the die-cast Al-Mg-Zn-Si alloy (a) solutionised at 430 °C for different times, (b) under as-cast condition and after being solutionised at 430 ºC for 60 min and aged at 160 °C for 90 min.

with standard deviation was obtained from 6 to 10 samples without showing obvious casting defects on the fractured surfaces. All tensile and hardness tests were performed at an ambient temperature (~ 20 °C).

The microstructure was examined using a Zeiss SUPRA 35VP scanning electron microscope (SEM) and a JEOL-2100F transmission electron microscope (TEM). To prepare thin foils for TEM examination, slices cut from the cast aluminium samples were mechanically ground and cut into 3 mm diameter discs. These discs were then ground to a thickness of less than 100 µm and finally ion-beam thinned on a Gatan precision ion polishing system at a voltage of 5.0 kV and an incident angle of 4–6°.

3. Results and discussion

Fig. 1a shows the mechanical properties of the Al-Mg-Zn-Si alloy after partial solution at 430 °C for different times. It was clear that the ultimate tensile strength (UTS) was only slightly increased from 350 MPa to 362 MPa over the different solutionising times. However, the elongation was significantly increased from 2.7% under as-cast condition to 5.5% after being solutionised for 60 min and further to 9.6% when the solution time was 150 min. Meanwhile, the yield strength was decreased from 220 MPa to 150 MPa. Obviously, the partial solution could significantly alter the elongation but reduce the yield strength. Furthermore, as shown in Fig. 1b, the yield strength, UTS and elongation was 285 MP, 386 MPa and 5.0%, respectively, for the Al-Mg-Zn-Si alloy after partial solutionising at 430 °C for 60 min and aged at 160 °C for 90 min. Compared with those under as-cast condition, the yield strength and elongation were simultaneously improved by the partial solution and subsequent ageing treatment.

Fig. 2 is the backscattered SEM microstructure of the Al-Mg-Zn-Si alloy under as-cast condition and after being solutionised at 430 °C for 60 min. It was clear that a large number of white $Mg_{32}(Al, Zn)_{49}$ intermetallics were located among the primary α-Al phase or between the eutectic cell and the primary α-Al phase in the as-cast samples (Fig. 2a and c). The $Mg_{32}(Al, Zn)_{49}$ intermetallics showed a sharp edge and irregular morphology. After the partial solution treatment, most of the white $Mg_{32}(Al, Zn)_{49}$ intermetallics were dissolved into the α-Al matrix (Fig. 2b), the volume fraction and sizes were dramatically decreased and the edges became blunt (Fig. 2d). On the other hand, the morphology and the volume fraction of Mg_2Si eutectic was maintained no change after partial solution due to the low solution temperature and short solution time, which indicated that the Mg_2Si eutectic would not provide positive effect on the improvement of mechanical property after partial solution. In addition, it should be noted that the mechanical properties of die-castings could be deteriorated when the solution temperature is too high and/or the solution time is too long [4], which results in the formation of blisters on the casting surface and overfired microstructure inside the castings. Therefore, the solution at 430 °C for 60 min was selected for further study because the results confirmed that the $Mg_{32}(Al, Zn)_{49}$ intermetallic was partially retained in the microstructure and the mechanical properties were improved in the subsequently aged Al-Mg-Zn-Si alloy.

In order to understand the strengthening mechanism, TEM and high resolution TEM (HRTEM) observations were performed for the Al-Mg-Zn-Si alloy after being solutionised at 430 °C for 60 min and subsequently aged at 160 °C for 90 min. The corresponding microstructural characteristics are presented in Fig. 3. It was obvious that a large number of fine precipitates ranged from 5 to10 nm were homogeneously distributed in the α-Al matrix (Fig. 3a). Further, the corresponding select area diffraction patterns (SADP) in the area under the $[112]_{Al}$ zone axis in Fig. 3b showed that several weak diffraction spots were located at the 1/3 and 2/3 220_{Al} positions in addition to the diffraction spots from the α-Al matrix. These typical diffraction information indicated that the fine precipitates were most likely the η'-$MgZn_2$ phase with a HCP structure, which was a metastable phase of $MgZn_2$ phase and was always found in Al-Zn-Mg-(Cu) alloys as the most important strengthening phase when the alloys reached a peak hardness [12,13]. Based on the SADP, the orientation relationships between the η'-$MgZn_2$ phase and the Al matrix could be described as $[\bar{1}2\bar{1}3]_{\eta'}\|[112]_{Al}$ and $(\bar{1}010)_{\eta'}\|(\bar{2}20)_{Al}$ (Fig. 3b). The corresponding fast Fourier transform (FFT) of HRTEM image was displayed at the lower right corner in Fig. 3c, where several clear diffraction streaks were also found at the 1/3 and 2/3 220_{Al} positions. Based on the previous research in the Al-Zn-Mg-Cu alloy [12,13], it was known that η'-$MgZn_2$ phases actually had four equivalent variants, and the η'-$MgZn_2$ phase in Fig. 3c only belonged to the one of four η'-$MgZn_2$ variants [13]. Therefore, its interface characteristics could be further analysed.

According to the obtained orientation relationships and HRTEM in Fig. 3, the spacing of $(\bar{3}030)_{\eta'}$ plane and $(\bar{1}2\bar{1}\bar{2})_{\eta'\eta'}$ plane were calculated as 0.148 nm and 0.241 nm, respectively. Therefore, the lattice parameters of η' precipitate could be deduced as: a=0.513 nm and c=1.409 nm, which were slightly bigger than the lattice parameters proposed by Kverneland (a=0.496 nm and c=1.402 nm) [14]. Furthermore, the lattice misfit δ between the η'-$MgZn_2$ precipitate and the Al matrix could be calculated as only 3.4% using the spacing of