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: High pressure die-casting alloys were not basically suitable for T6 treatment. The partial solution treatment was developed to enhance the mechanical properties for a new designed die-cast Al-Mg-Zn-Si alloy. The strengthening mechanism was that the $Mg_{32}(Al,Zn)_{49}$ intermetallics and equilibrium $MgZn_2$ phase formed in the as-cast microstructure were partially dissolved into the α-Al matrix during solutionising and the fine semi-coherent η'-$MgZn_2$ phases were precipitated during subsequent aging. Consequently, a unique microstructure was obtained by the co-existence of equilibrium $MgZn_2$ 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.

Key Word: Aluminium alloys; Mechanical property; Microstructure; Heat treatment; High pressure die-casting.

The application of thin-wall components made by high pressure die-casting of aluminium alloys is one of the preferred options to make light weight structures in automotive industry [1,2]. However, the existing die-cast Al 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 [3,4]. This has been partially attributed to the presence of substantial amount of porosity in die-castings, which result in the inapplicable of standard full solution and ageing treatment to enhance the mechanical properties [5,6]. Although a quick solution treatment process was developed for die-cast Al-Si-Cu alloys to eliminate blistering and porosity [7, 8], the elongation of the existing Al-Si-Cu alloys is still hardly satisfied by industrial requirements.

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 [9]. One of the significant advantages was that the alloy was designed for precipitation strengthening through solutionising and ageing. However, when a solutionising process at 490-510ºC 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 ºC [5]. Therefore, it is essential to develop a new heat treatment for the Al-Mg-Zn-Si alloy to improve simultaneously the yield strength and elongation without overfiring or forming blisters. In this paper, we study 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.

The die-cast Al-10.2Mg-2.7Si-3.2Zn (wt.%) alloy was prepared and cast in a 4500 KN high pressure die casting machine. The partial solution was performed at 430 ºC for different times, and subsequent ageing was performed at 160 ºC for 90 min. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to analyse the mechanism of improving the mechanical properties.

Figure 1a shows the mechanical properties of the Al-Mg-Zn-Si alloy after partial solution at 430 ºC 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 Figure 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 solution at 430 ºC for 60 min and aged at 160 ºC for 90 min. Compared with those under as-cast condition, the yield strength, UTS and elongation was increased by 29.5%, 10.3% and 85.2%, respectively. Clearly, the yield strength and elongation could be simultaneously improved by the partial solution and subsequent ageing treatment.

Figure 2 is the backscattered SEM microstructure of the Al-Mg-Zn-Si alloy under as-cast condition and after being solutionised at 430 ºC 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 (Figure 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 (Figure 2b). the volume fraction and sizes were dramatically decreased and the edges became blunt (Figure 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 the 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 blisters formed on the casting surface and overfired microstructure are two critical detrimental factors to affect the mechanical properties of die-cast alloys. If the solution temperature was high and/or the solution time was long, the mechanical properties of die-castings was deteriorated [5]. Therefore, the solution at 430 ºC for 60 min was selected for further study because the $Mg_{32}(Al,Zn)_{49}$ intermetallics 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 ºC for 60 min and subsequently aged at 160 ºC for 90 min. The corresponding microstructural characteristics are presented in Figure 3. It was obvious that a large number of fine precipitates with 5-10 nm size were homogeneously distributed in the α-Al matrix (Figure 3a). Further, the corresponding select area diffraction patterns (SADP) in the area under the $[112]_{Al}$ zone axis in Figure 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' phase with a HPC 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 [10][11]. Based on the SADP, the orientation relationships between the η' phase and the Al matrix could be described as $[\bar{1}2\bar{1}3]_{\eta'}//[112]_{Al}$ and $(\bar{1}010)_{\eta'}//(\bar{2}20)_{Al}$ (Figure 3b). The corresponding fast Fourier transform (FFT) of HRTEM image was displayed at the lower right corner in Figure 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 [10][11], it was known that η' phases actually had four equivalent variants, and the η' phase in Figure 3c only belonged to the one of four η' variants [11]. Therefore, its interface characteristics could be further analysed.

According to the obtained orientation relationships and HRTEM in Figure 3, the spacing of $(\bar{3}030)_{\eta'}$ plane and $(\bar{1}2\bar{1}2)_{\eta'}$ 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 a little bigger than the lattice parameters proposed by Kverneland (a = 0.496 nm and c = 1.402 nm) [12]. Furthermore, the lattice misfit δ between the η' precipitate and the Al matrix could be calculated as only 3.4% using the spacing of two parallel crystal planes $(\bar{3}030)_{\eta'}$ and $(\bar{2}20)_{Al}$. The 4.3% misfit indicated that the η' precipitates had a semi-coherent interface with the Al matrix, which inevitably introduced a strain field in the surroundings in the Al matrix. Figure 3d showed the strain map of η' precipitates in the α-Al matrix calculated by Geometric Phase Analysis in $[\bar{2}20]_{Al}$ direction. A maximum 5%

tensile strain was found at the interface, as marked by an ellipse in Figure 3d. Therefore, the η' precipitates could become the effective obstacles of dislocation movement to strengthen the Al-Mg-Zn-Si alloy.

Furthermore, in order to understand the behaviour of precipitates phase in the α-Al phase, TEM images were taken for the alloy under as-cast and under partial solution and aged conditions, as shown in Figure 4. It was seen that numerous plate-shaped equilibrium η-$MgZn_2$ phase with 200~300 nm long were found in the as-cast microstructure (Figure 4a). After the partial solution and ageing, in addition to a large number of fine η' precipitates, a portion of equilibrium η-$MgZn_2$ phase still existed in the α-Al matrix (Figure 4b). The co-existence of fine η' precipitates and equilibrium η-$MgZn_2$ phase is unique microstructural features for the partially solutionised and aged Al-Mg-Zn-Si alloy, which not only can improve the elongation, but also can enhance the yield strength because of the precipitation of fine semi-coherent η' phases. In the meantime, the relatively low solutionising temperature is preferred because it can retard the formation of blisters on the casting surface and benefit the dimensional stability of die-casting Al alloys.

In conclusion, the partial solution treatment of die-cast Al-Mg-Zn-Si alloy is effective to control the improvement of yield strength and elongation simultaneously, which also benefits the reduction of porosities and blisters by applying relatively lower solutionising temperature and shorter time in comparison with the conventional solutionising process. The strengthening mechanism is that the equilibrium $MgZn_2$ phase in the α-Al phase and the $Mg_{32}(Al,Zn)_{49}$ intermetallics formed in the as-cast microstructure are partially dissolved into the α-Al matrix during solutionising, and fine metastable η' phases are precipitated from the α-Al matrix in the subsequent aging. This unique microstructure is characterised by the co-existing of equilibrium $MgZn_2$ and metastable η' phase in the primary α-Al phase, together with the un-changed Mg_2Si eutectic and remnant $Mg_{32}(Al,Zn)_{49}$ intermetallics in the die-cast Al-Mg-Zn-Si alloy.

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Figure(s)

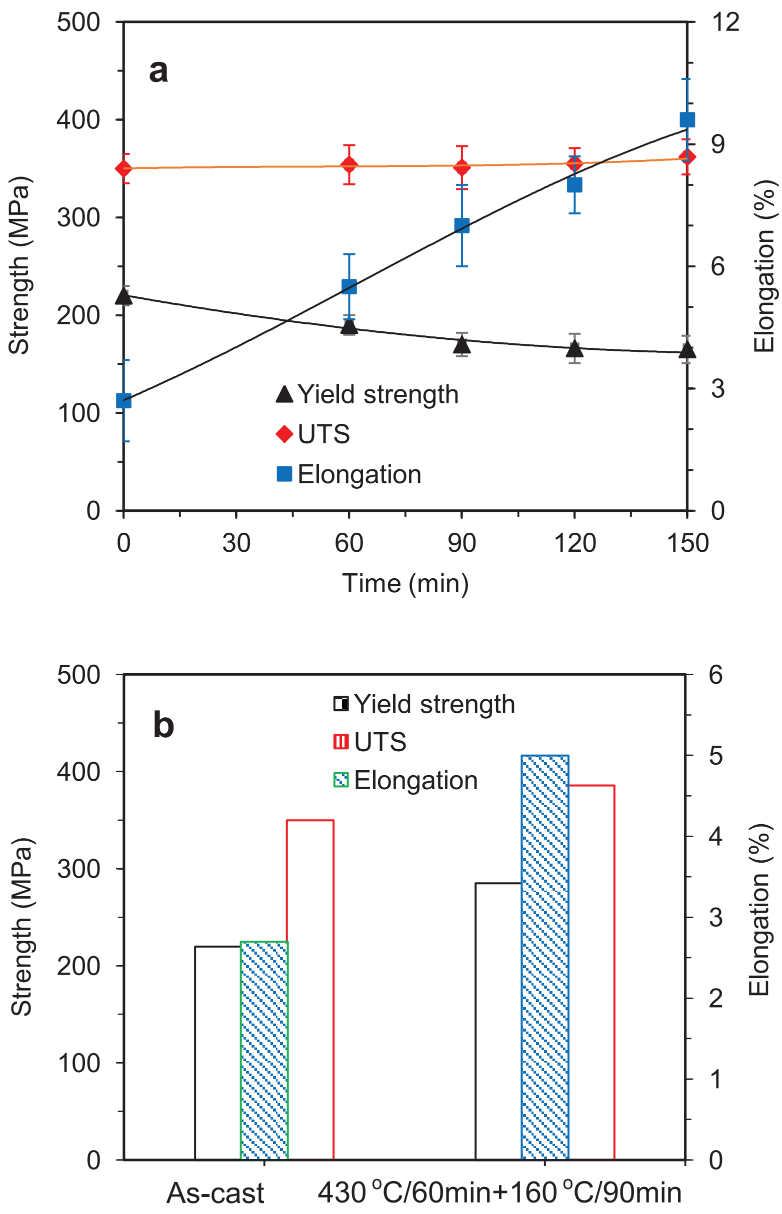

Figure 1. Mechanical properties of the die-cast Al-Mg-Zn-Si alloy (a) solutionised at 430 °C for different times, (b) under as-cast condition and after being solutionised at 430 °C for 60 min and aged at 160 °C for 90 min.

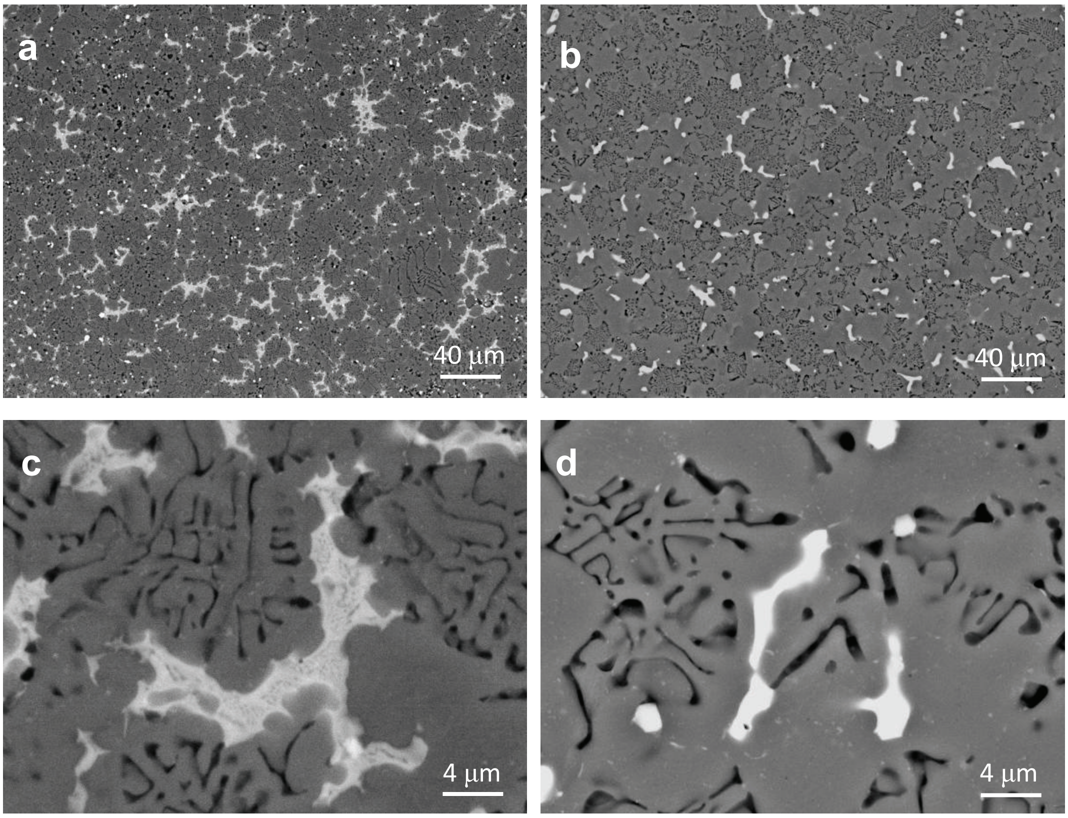

Figure 2. Backscattered SEM images of the Al-Mg-Zn-Si alloy (a, c) under as-cast condition, (b, d) after being partially solutionised at 430 ºC for 60 min and subsequently aged at 160 ^{o}C for 90 min.

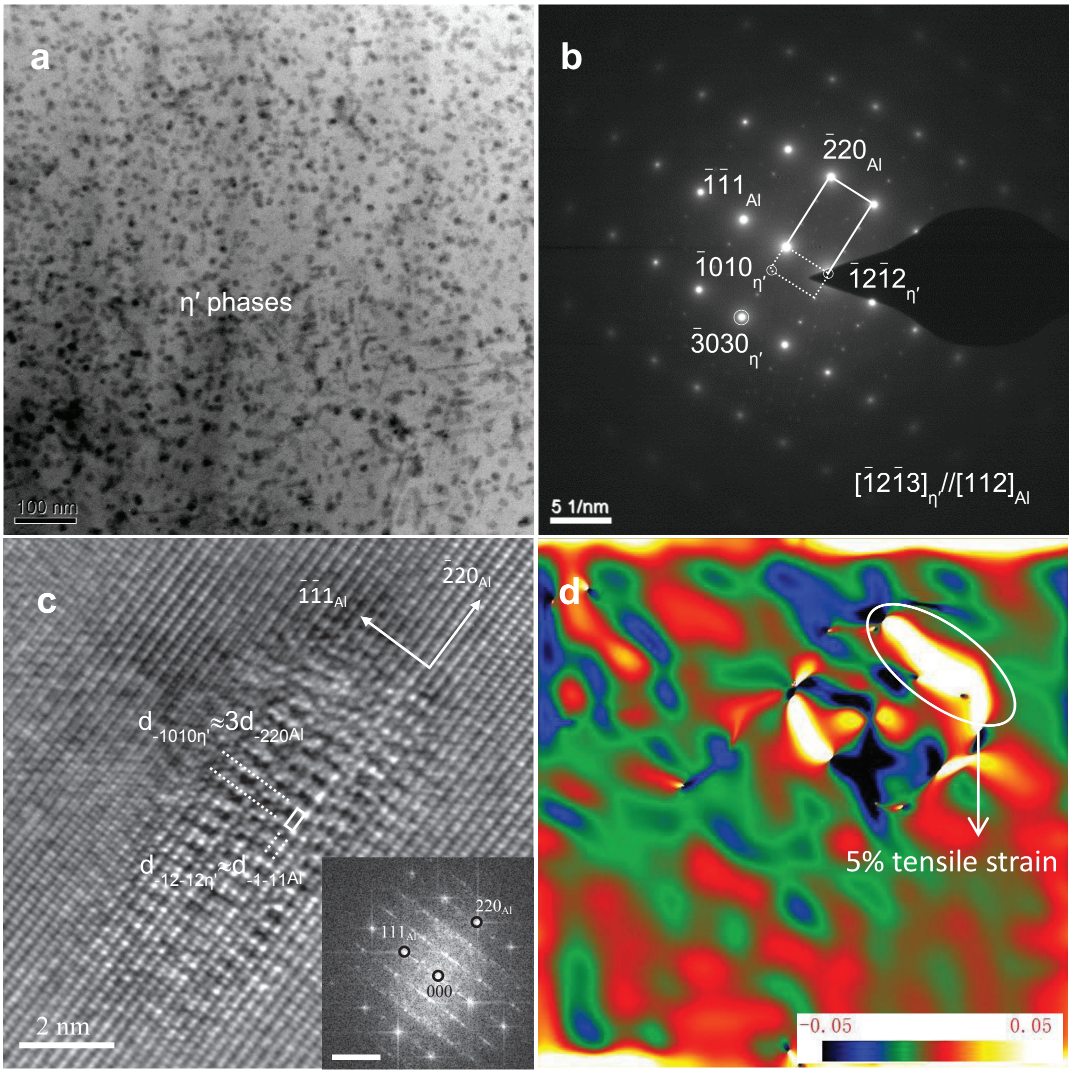

Figure 3. TEM and HRTEM micrographs of the die-cast Al-Mg-Zn-Si alloy after being solutionised at 430 °C for 60 min and aged at 160 °C for 90 min. (a) TEM image of fine η′ phase precipitated from Al matrix, (b, c) the corresponding SADP and HRTEM of η′ phase, (d) strain map along the $[\bar{2}20]_{Al}$ direction. The corresponding FFT of HRTEM image was displayed at the lower right corner in (c).

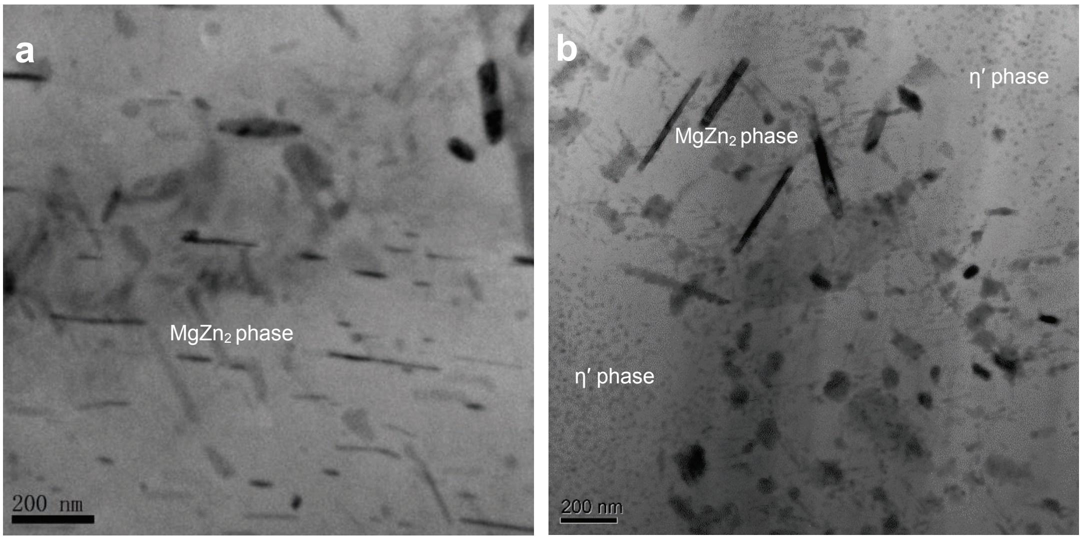

Figure 4. TEM micrographs showing the morphology and sizes of precipitates in α-Al phase of the die-cast Al-Mg-Zn-Si alloy (a) under as-cast condition and (b) after being solutionised at 430 ºC for 60 min and aged at 160 ^{o}C for 90 min.

*Graphical Abstract