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EFFECT OF ZR AND V ADDITIONS ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF THE ALSI10MG CAST ALLOY

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ABSTRACT

The microstructure of Al-10Si-0.3Mg-0.5Mn alloy with 0.27% Zr and 0.19% V addition was quantitatively analysed and compared to the base material. The addition of Zr and V in the AlSi10Mg alloy exhibit a beneficial effect on the Si modification, resulting in the reduction of the size of eutectic Si particles on both as-cast and T6 conditions. The quantitative image analysis results show that the Zr and V addition and T6 treatment can reduce the size of the intermetallic phases. In addition, the presence of Zr and V is favour to the partial dissolution of the intermetallic phases during the T6 treatment. Different heat treatment procedures were tested to optimize treatment parameters. The mechanical properties of the alloys were evaluated using hardness measurements and tensile tests. The results show that the addition of Zr and V can remarkably improve the mechanical properties on as-cast and T6-treated conditions. The correlation between the microstructure and mechanical properties of the alloys is discussed.

KEYWORDS

AlSi10Mg foundry alloy, Heat treatment, Mechanical properties, Microstructure

INTRODUCTION

Al-Si-Mg foundry alloys have been widely used in automotive and aerospace industries due to their high strength-to-weight ratio, heat-treatable capability and excellent castability. The alloying elements such as Cu, Mn, Fe are traditionally added into Al-Si-Mg alloys to improve their mechanical properties (Mohamed, Samuel, Samuel & Doty, 2009). In recent years, the attention has been paid to the effect of the transition elements such as Zr, V, Ti, etc, as minor alloying additives, on the properties of aluminum alloys (Elhadari, Patel, Chen, & Kasprzak, 2011; Kasprzak, Amirkhiz & Niewczas, 2014; Shaha, Czerwinski, Kasprzak, Friedman & Chen, 2015; Shaha, Czerwinski, Kasprzak & Chen, 2014; Mahmudi, Sepehrband, Ghasemi & 2006; Meng, Cui, Zhao & Zuo, 2013). Kasprzak et al., (2014) and Shaha et al., (2015) reported that additions of Zr, V, and Ti in Al-Si-Cu-Mg cast alloys can improve the alloy mechanical properties at high temperature by forming stable intermetallics and precipitates on as-cast and heat treatment conditions. On the other hand, the mechanical properties of near-eutectic and eutectic Al–Si cast alloys depend not only on the chemical composition but also, even more importantly, on microstructural features such as the morphology and size of eutectic silicon and intermetallic particles, which are present on both as-cast and heat treatment conditions (Mohamed et al., 2009). However, there is rather limited information on the effect of Zr and V on the microstructure features and mechanical properties of near-eutectic Al-Si-Mg cast alloys.

The aim of the present work is to reveal the effect of Zr and V addition on microstructure features and mechanical properties of an AlSi10Mg cast alloy by quantitative microstructure characterization as well as the evaluation of electron conductivity and mechanical properties on as-cast and heat treatment conditions.

EXPERIMENTAL

Two AlSi10Mg experimental alloys were designed in the current study. One of the alloys was with Zr and V addition, referred as HPD101, while the other one is without containing Zr and V as the base alloy. Commercially pure Al (99.7%), pure Mg (99.9%), Al-25%Mn, Al-25%Fe, Al-50%Si, Al-5%V and Al-15%Zr master alloys were used in the alloy preparation. For each batch, approximately 3 kg of materials were melted in an electrical resistance furnace. The melt was kept at 750ºC for 30 min and degassed for 15 min. The melt was then poured into a copper permanent mold preheated at 250ºC. The dimension of the cast plates is 100 mm x 80 mm with a wall thickness of 4 mm. The chemical compositions of the experimental alloys analyzed by an optical emission spectrometer are listed in Table 1.

Table 1. Chemical compositions of experimental alloys (wt.%)

Alloy	Si	Mn	Mg	Fe	Ti	Sr	Zr	V	Al
Base	10.20	0.52	0.31	0.16	0.08	0.011	0.00	0.02	bal.
HPD 101	10.17	0.48	0.36	0.16	0.08	0.011	**0.27**	**0.19**	bal.

To optimize the T6 heat treatment parameters, the alloys were heat-treated with a heating rate of 5ºC/min to 500ºC or 540ºC and then held for 2 h, 4 h and 8 h, respectively, followed by water quench. The aging treatment was performed at 170ºC for 4 hours.

Conventional metallographic polishing method was used to prepare samples for microstructure observation. The microstructures were examined using an optical microscope (Nikon, Eclipse ME600) equipped with an image analyzer (CLEMEX software), and a scanning electron microscope (SEM, JSM-6080LV) coupled with energy-dispersive X-ray spectroscopy (EDS).

To evaluate the mechanical properties, Vickers microhardness and tensile tests were carried out. Vickers microhardness tests were performed with a load of 300 g and a dwelling time of 15 s according to ASTM-E92. Sub-size tensile test bars with 100 mm in overage length and 25 mm in gage length were machined from the cast plates based for the tensile testing according to ASTM-B557M. The tensile properties were reported as the average values of the ultimate tensile strength (UTS), yield strength (YS) at a 0.2% offset strain and fracture elongation (El) from four test bars. Electrical conductivity was measured using Sigmascope SMP10 unit, and the average data were reported over at least five measurements.

RESULTS AND DISCUSSION

Microstructure of the Base Alloy and Zr and V Containing Alloy

Figures 1–3 show the typical microstructures of the base and HPD101 alloys on as-cast condition. The microstructures of base and HPD101 alloys are consisted of dendrite-like aluminum cells/grains, Al-Si eutectic, primary Mg_2Si phase and different types of intermetallic phases (arrows indicated in Figure 1). Although Sr was added in both alloys to modify eutectic Si phase, a considerable amount of Si particles in the base alloy are still plate-like. The most of eutectic Si in the HPD alloys were fully modified and showed the fiber-like morphology (Figure 1), indicated that the Zr and V addition are favor to the modification of Si phase. The long needle-like intermetallic phase was observed in base alloy (Figures 1a and 2a). The chemical composition of the intermetallic phases was analyzed with EDS-SEM, composed of Al, Fe, Si and Mn, refereed as Fe-rich intermetallic phase (Figure 2b). In the HPD101 alloy, three distinct intermetallic phases with different morphologies were found (Figure 3a). The corresponding spectrums of these intermetallics are shown in Figures 3b and c. The rod-like phase is composed of Al, Zr, Si, and Ti, refereed as Zr-rich intermetallics. The elements, Al, V and Si, were detected in the block-like phase, which is refereed as V-rich intermetallics. In addition to the needle-like Fe-rich intermetallic phase, the Zr and V addition generated its own intermetallics although their amount is limited.

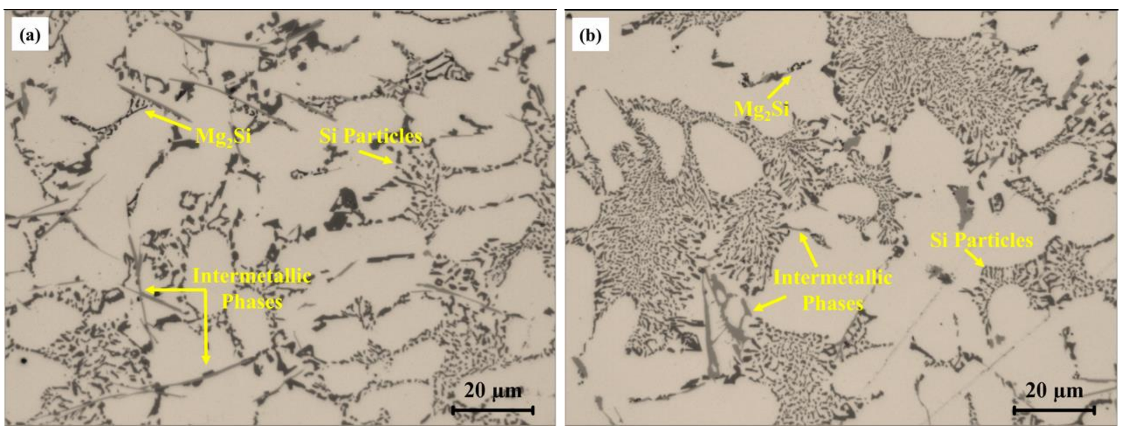

Figure 1. Optical microstructure images of the base alloy (a) and HDP101 alloy (b)

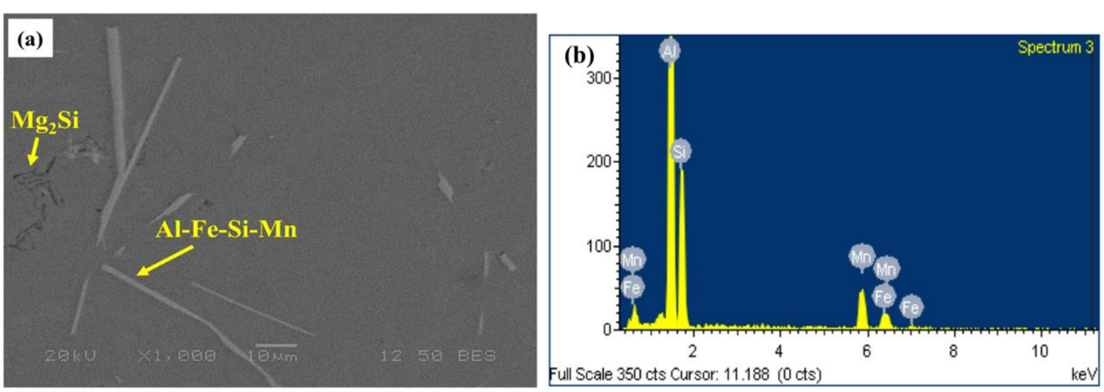

Figure 2. SEM backscattered electron image of the base alloy (a) and EDS spectrum of Fe-rich phase (b)

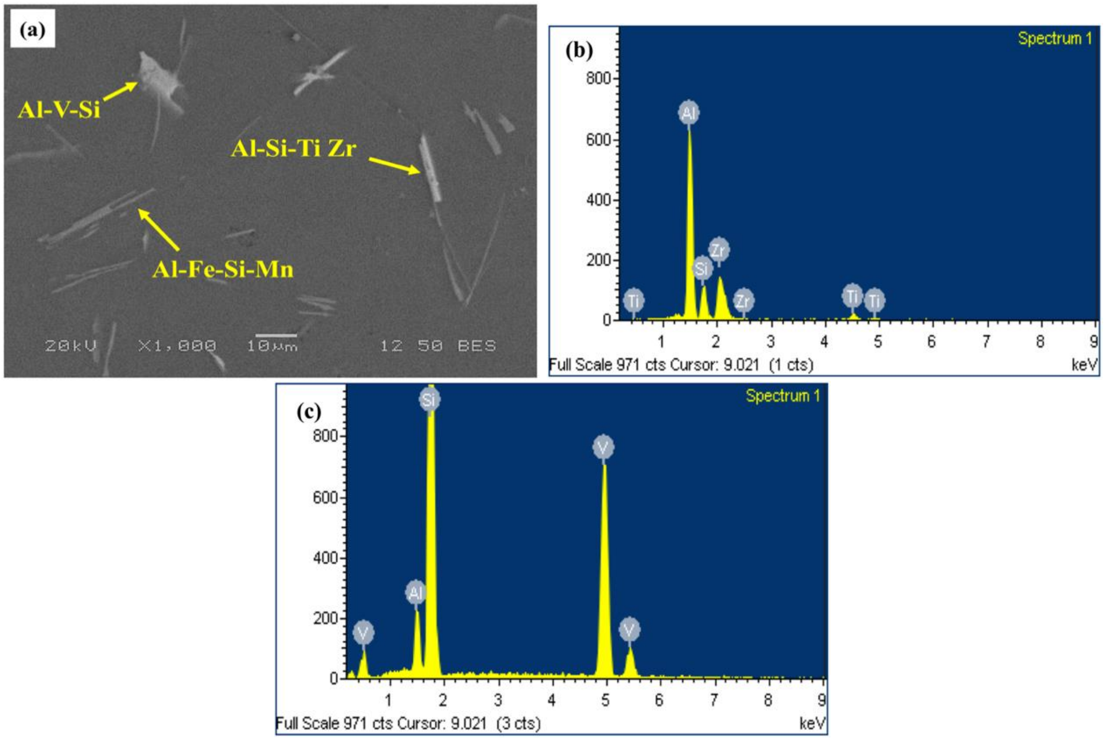

Figure 3. SEM backscattered electron image of HPD101 alloy (a), and EDS spectrum of Zr-rich intermetallic phase (b), and V-rich intermetallic phase (c)

The typical microstructures after T6 treatment (540ºC for 2 h plus 170 ºC for 4 h) in both base and HPD101 alloys are given in Figures 4 and 5. The eutectic Si particles became spheroidized in both alloys (Figure 4). The needle-like Fe-rich intermetallic phase was still present in the base alloy whereas block-like V-rich intermetallic, rod-like Zr-rich intermetallic and needle-like Fe-rich intermetallic phases were observed in the HPD101 alloy (Figure 5). Due to high thermal stability of those intermetallic phases, the solution treatment at 540ºC may not change such phases. However, the size of those intermetallic particles after T6 becomes smaller in both alloys compared to the as-cast condition. In a general view, the T6 treatment can change the Si morphology and reduce the size of intermetallic particles in both alloys.

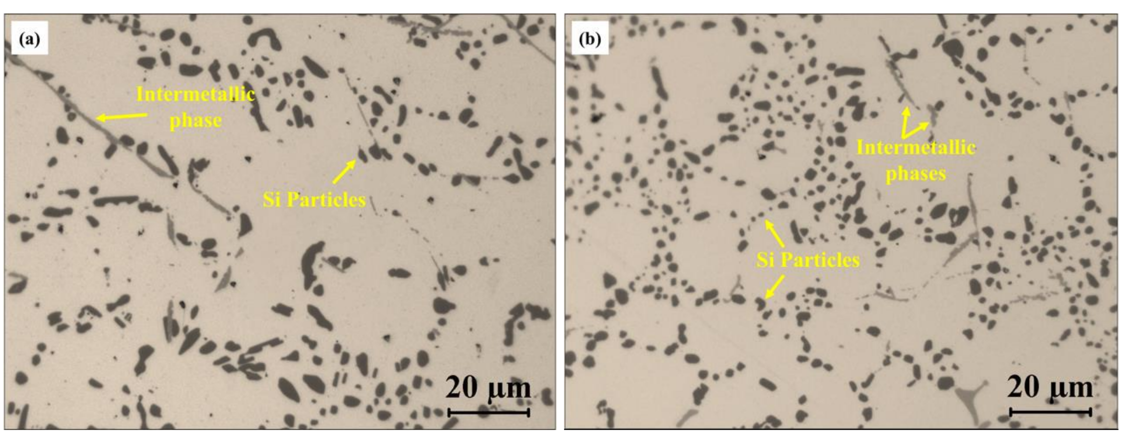

Figure 4. Optical images of the base and HPD101 alloys on heat treated condition

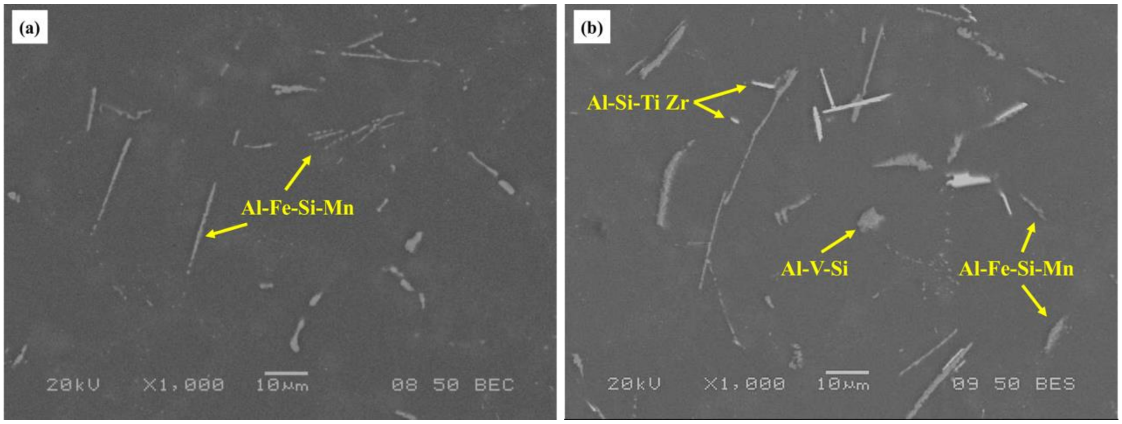

Figure 5. SEM backscattered electron images of the base (a) and HPD101 (b) alloys after T6

Quantitative image analysis of Si and intermetallic phases was performed to reveal the effect of Zr and V addition on the phase morphology and size on as-cast and T6 conditions. Figure 6 shows the equivalent diameter of Si particles in the base and HPD101 alloys. The equivalent diameter of Si particles in the HPD101 alloy is smaller than that in the base alloy on both as-cast and T6 conditions, attributed to the beneficial effect of Zr and V on the Si modification (see Figure 1). After T6 heat treatment, the morphology of Si has changed, and however, the equivalent diameter of Si particles in two alloys becomes larger. This suggests that the additions of Zr and V can reduce the size of Si particles in the AlSi10Mg alloys and the T6 heat treatment can further change the Si morphology and promote the spheroidization. However, the coarsening of Si particles occurs during the heat treatment.

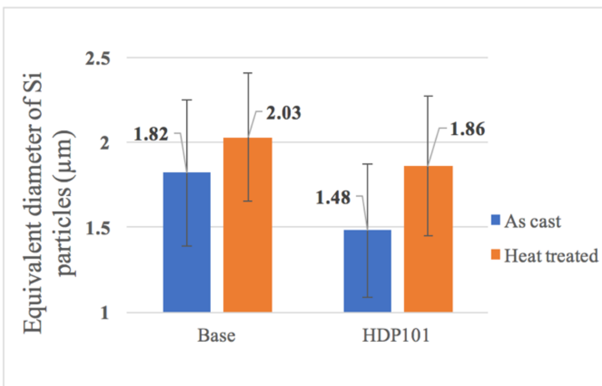

Figure 6. Equivalent diameter of Si particles in the base and HPD101 alloys on as-cast and T6 heat treatment conditions

The aspect ratio, length and volume fraction of intermetallic phases in two alloys are illustrated in Figure 7. It is found that the aspect ratio and the length of intermetallic phases in the HPD101 alloy are smaller and shorter than that in the base alloy on both as-cast and T6 conditions. The T6 heat treatment further decreases the aspect ratio and length of the intermetallic phases in two alloys. This implies that the Zr and V addition and T6 treatment can reduce the size of the intermetallic phases in the AlSi10Mg alloys.

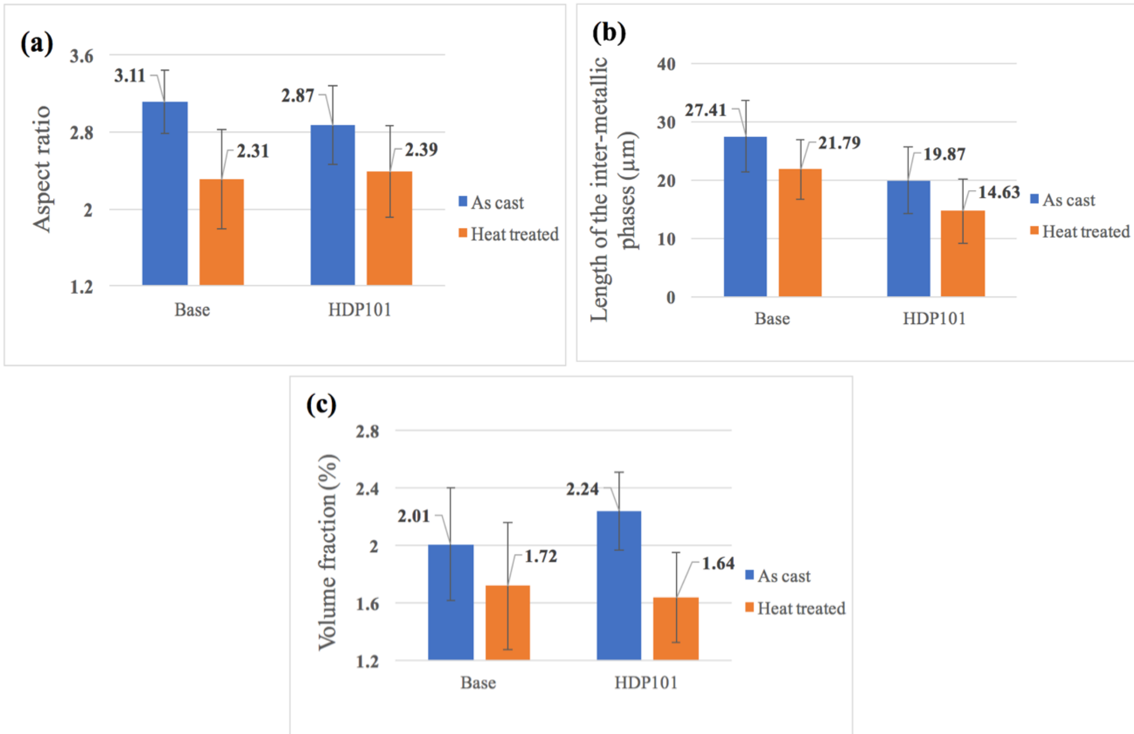

Figure 7. The aspect ratio (a), length (b) and volume fraction (c) of the intermetallic phases in the base and HPD101 alloys on as-cast and T6 heat treatment conditions

The quantitative image analysis results also show that the addition of V and Zr increases slightly the volume fraction of intermetallic phases on as-cast condition (Figure 7c), which is attributed to the formation of V-rich and Zr-rich intermetallic phases. On the other hand, the volume fraction of intermetallic phases in the two alloys after T6 becomes less than that on as-cast condition, most likely due to the fragmentation and partial dissolution of intermetallic phases. It is interesting to note that after T6, the volume fraction of intermetallic phases in the HPD101 alloy is even less than that in the base alloy. This implies that the Zr and V addition is favour to the partial dissolution of intermetallic phases during heat treatment, resulting in more solute elements in the aluminum matrix.

Mechanical Properties of the Base Alloy and Zr and V Containing Alloy

Mechanical Properties on As-Cast Condition

The mechanical properties of the base and HDP-101 alloys were determined with Vickers hardness measurement and tensile tests in the room temperature. On the as-cast condition, the average hardness of the base alloy is ~ 76.4 HV while it is ~ 85.1 HV in the HPD101 alloy, illustrating a clear benefit of the Zr and V addition on the hardness of the AlSi10Mg alloys. As shown in Figure 8, the tensile properties of the HPD101 alloy are clearly better than those of the base alloy on the as-cast condition. The increases of YS, UTS and El for the Zr and V containing alloy (HDP-101) are 28%, 29% and 25%, respectively. It is the evidence that the addition of Zr and V can considerably improve the hardness and tensile properties of AlSi10Mg alloys on as-cast condition. The improvement of mechanical properties is likely attributed to: (1) the reduction of the size of intermetallic phases as well as the refinement of eutectic Si particles (Figures 6 and 7), which are favour to the decrease of the stress concentrations in aluminum matrix; (2) the solid solution strengthening of Zr and V. Except some of Zr and V bounded in the intermetallic phases, most of them are still in the solid solution of as-cast aluminum matrix. The measurements of the electrical conductivity (EC) show that the electron conductivity of the HPD101 alloy

(16.3 MS/m) is remarkably lower than that of the base alloy (19.28 MS/m), confirming that most of Zr and V are as solute atoms in the aluminum matrix.

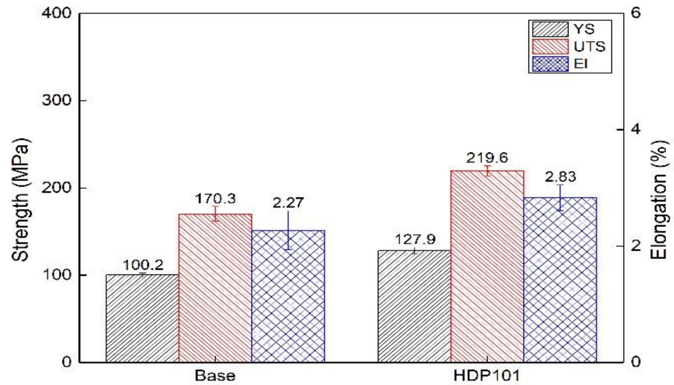

Figure 8. Tensile properties of the base and HPD101 alloys on as-cast condition

<u>Mechanical Properties on T6 Condition</u>

In order to find the optimum T6 treatment condition, two solution temperatures (500ºC vs 540ºC) with the same aging parameter (170ºC/4h) were selected for the investigation. Figure 9 shows the hardness evolution as a function of the holding time at two temperatures. Solution-treated at 500ºC, the hardness increase with increasing holding time and up to 8 h it reaches 104.6 HV for the base alloy and 116.6 HV for the HPD101 alloy, respectively. At 540ºC, the hardness increases rapidly in the first 2 hours in both alloys and then follows a plateau. In general, the alloys treated at 540ºC (Figure 9b) exhibit higher hardness values than those at 500ºC (Figure 9a). At both solution temperatures, the hardness of HPD101 is always higher than that of base alloy. Thus, the T6 treatment condition of 540ºC/2h plus 170ºC/4h aging was chosen for further tensile testing.

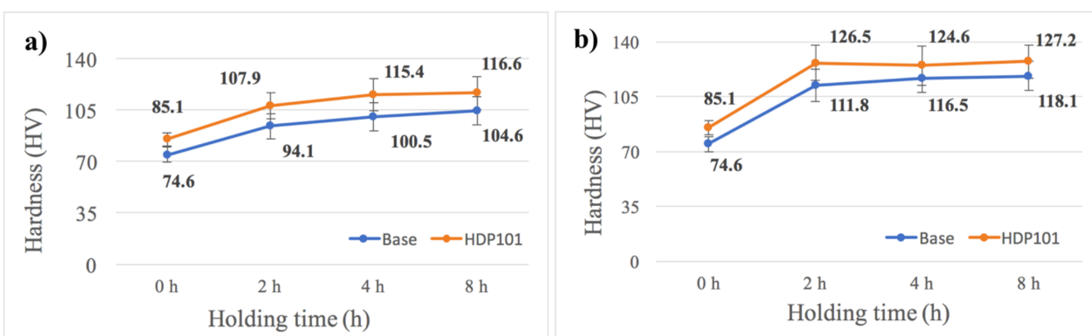

Figure 9. Evolution of hardness as a function of holding time at solution temperatures of a) 500ºC and b) 540ºC

Tensile properties of the T6-treated alloys are given in Figure 10. Compared to the as-cast condition (Figure 8), the tensile properties after T6 are significantly improved. For example, the YS of both alloys after T6 increase more than double. On the other hand, it is also obvious that all tensile properties of the HPD101 alloy are higher than those of the base alloy. The increase of tensile properties is 18% for YS, 25% for UTS, and 128% for EL, respectively. A few of factors can contribute the improvement of mechanical properties after T6 treatment in the Zr and V containing alloy, which include: (1) the reduction of the length and volume fraction of intermetallic phases (Figure 7); (2) the high supersaturation of solid solution due to the favourable partial dissolution of intermetallic phases during heat treatment, which increases both the solid solution strengthening and precipitation strengthening; and (3) the promotion of the precipitation due to the presence of Zr and V solute atoms in the solid solution, which will be confirmed in the future research work using TEM investigation.

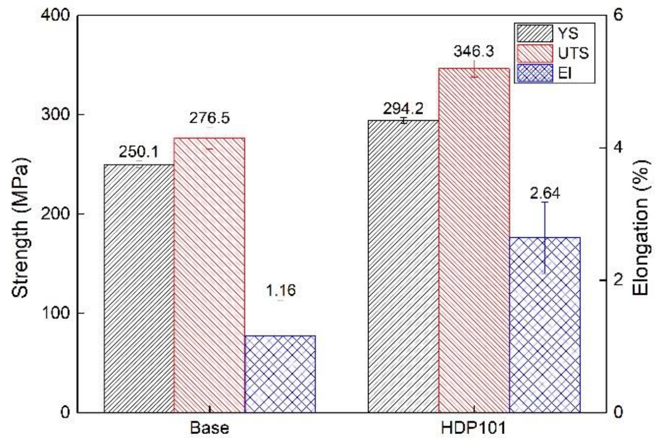

Figure 10. Tensile properties of the base and HPD101 alloys on T6 condition (540ºC/2h solution plus 170ºC/4h aging)

CONCLUSIONS

(1) The addition of Zr and V in the AlSi10Mg alloy has a beneficial effect on the Si modification, resulting in the reduction of the size of eutectic Si particles on both as-cast and T6 conditions.

(2) The addition of Zr and V reduces the aspect ratio and length of intermetallic phases in the microstructure. In addition, it is favour to the partial dissolution of the intermetallic phases during T6 treatment.

(3) The hardness and tensile properties of the AlSi10Mg alloy are remarkably improved by the Zr and V addition on both as-cast and the T6 conditions.

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