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EFFECT OF TRANSITION ELEMENTS ADDITIONS ON MICROSTRUCTURE AND TENSILE PROPERTIES OF A SECONDARY Al-7Si-Mg CAST ALUMINIUM ALLOY

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ABSTRACT

The economic and environmental benefits of recycling aluminium alloys have increased the need to consider re-designing the alloys. The key challenge in recycling Al alloys is the varied chemical composition of the Al scrap. The effect of Ti, Sr, Cu and transition elements Zr and V additions on tensile properties of secondary cast 356 Al-Si alloy has been investigated with the aim of designing and producing premium automotive parts such as cylinder heads. The secondary cast 356 Al-Si alloy (base alloy) and its variant 356 + 0.5Cu + X (X = 0.15% Ti + 0.15% Zr + 0.25% V + 0.015% Sr) was cast, HIP ped and T6 heat treated. There was notable improvement in the ultimate tensile strength (UTS) and Yield strength (YS) of the base alloy upon addition of the elements. At room temperature, the UTS improved from 224 MPa to 279.3 MPa while the YT improved from 210 MPa to 268 MPa. At high temperature (237°C), the UTS and YT improved from 149 MPa to 186 MPa and from 122 MPa to 167 MPa respectively. These improvements in strengths were however accompanied by a decrease in percent elongation, from 5% to 4.4% and from 8% to 6.8%, at room and high temperatures respectively. The decrease in ductility with the element addition can be attributed to the increased amount of course brittle intermetallic phases. At high temperature (237 ^{0}C), the strengthening phases in the base alloy undergo Ostwald ripening thus resulting in lower UTS and YT. On the other hand, the micro sized tri-aluminide phases are stable at high temperature (237°C) explaining the substantial improvement in yield strength of 36.9%.

Keywords: Al-Si alloys, Heat Treatment, Microstructure, Tensile properties.

1. INTRODUCTION

Al-Si alloys have become a suitable alternative to cast iron in the fabrication of automobile chassis and powertrain components e.g. wheels, cylinder heads, engine blocks and pistons. This has been driven by the continuous need to reduce vehicle weight, increase fuel efficiency, improve vehicle performance and reduce CO_2 emissions alongside conservation of the environment [1], [2]. Al-Si alloys have attractive properties which include, high specific strength and stiffness, excellent thermal conductivity, good wear resistance, good recyclability and castability [3]–[6].

To improve on efficiency and performance, modern automotive engines require high operating temperatures (>250°C) and pressure (>180 bar) [7], [8]. These operating conditions subject the engine components to thermomechanical fatigue. High temperatures (above 200°C) also lead to a decline in the strength of the conventional Al-Si-Cu, Al-Si-Mg and Al-Si-Cu-Mg alloys. This is due to the rapid coarsening (Ostwald ripening) and dissolution of the strengthening phases Al_2Cu, Mg_2Si and/or Al_2CuMg [2], [4], [9]–[13]. According to Knipling [14], for effective high temperature performance of Al alloys, the alloying elements should have low solid solubility and diffusivity in the Al matrix. Transition elements such as Ti, Zr, V, and Cr have been reported to be the best candidates for the formation of thermally stable phases [2], [8], [14]. These transition elements precipitate in the form of Al_3X-trialuminide phases of cubic $L1_2$ structure (chemically and structurally analogous to Ni_3Al in the Ni-based superalloys) and tetragonal structures DO_{22}/DO_{23} [1], [8], [14].

The role of these transition elements in cast Al-Si alloys has recently been a subject of research [1]–[4], [11], [14]–[18]. Shaha et al. [3], [19] and Elhadari [11] reported that micro-additions of Cr, Zr, Ti and V significantly improved the fatigue life, yield strength (YS) and ultimate tensile strength (UTS) of Al-7Si-Cu-0.5Mg alloy compared to that of A356-T6 alloys both at room and high temperatures. Zamani et al. [4] stated that addition of Zr, Ni, Ti, V and Cr to Al-10Si alloy resulted in a significant improvement in tensile strength at 250°C, but at the expense of ductility. They attributed the reduction in ductility to the presence of coarse brittle phases such as $(AlSi)_3(TiZr)$, $(AlSi)_3(CrVTi)$, AlNbTiZr and AlSiV.

These improvements in mechanical properties are attributed to the precipitation strengthening by thermally stable nano-sized Al_3(Cr/Ti/Zr/V)-trialuminide precipitates, which are uniformly distributed in the aluminium matrix. These precipitates effectively hinder the movement of dislocations during tensile loading resulting in an improvement of the alloy strength [1]–[4], [11], [14]–[18]. The improvement in the mechanical properties Al-Si alloys containing micro additions of Ti/Zr/V has also been associated to their grain refining effect [2], [16], [18], [20]–[25]. However, Elhadari [11] observed that minor additions (<0.25 wt. %) of Zr and V yielded minimal grain refinement and that for effective grain refinement, the levels of Zr should be increased to ~0.3 – ~0.69 wt.%.

Previous works involving transition element additions have majorly concentrated on primary Al alloys [4], [11], [14]–[18]. The ecological and economic benefits of recycling aluminium alloys [26] has seen a lot of attention directed towards the possibility of using secondary aluminium alloys in producing premium automotive components (e.g. wheels, engine blocks, pistons and cylinder heads). However, the effect of transition elements on the microstructure and mechanical properties of secondary Al-Si alloys, that generally have higher impurity metal content, is not well understood. This work therefore seeks to investigate the effect of a combined element addition of Ti, Sr, Zr, V and Cu on the microstructure and mechanical properties of secondary 356 alloys.

2. EXPERIMENTS

The Secondary cast 356 Al-Si alloy used in this work was obtained from casting after-life aluminium wheels. The alloy was melted and poured into a permanent mould and upon solidification, a bar casting obtained as shown in Figure 1. Optical Emission Spectroscopy (OES) was used to obtain the chemical compositions of the base alloy and the modified alloy. The various elements were added using master alloys (Al-10 wt% Sr, Al-15 wt.%Ti, Al-5 wt.%V, Al-10 wt.% Zr, and Al-50 wt. % Cu) to the base alloy. The chemical compositions are given in **Error! Reference source not found.**. Before specimens were prepared for testing, the castings were subjected to HIPping (holding at 520°C and 100 MPa for 3 hours) followed by T6 heat treatment (solutionizing at 500 °C for alloys without Cu addition and 540 °C for Cu-rich alloys, quenching in hot water at 60°C and immediate aging at 190°C for 100 hours followed by air-cooling).

Figure 1: The bar casting obtained after the melt had solidified inside the permanent mould.

Table 1: Chemical composition (in wt.%) of secondary 356 cast aluminium base alloy with transition element modification.

Alloy	Si	Cu	Mg	Fe	Mn	Cr	Ti	Zr	V	Sr	Al
356 (Base alloy)	6.95	0.0887	0.445	0.210	0.158	0.0174	0.0589	0.0040	0.0072	0.0009	Bal
356+0.5Cu+X	6.67	0.5611	0.533	0.192	0.117	0.070	0.160	0.102	0.219	0.0156	Bal

X=0.15%Ti+0.15%Zr+0.25%V+0.015%Sr

Tensile tests were performed on an Instron 300DX universal testing machine at room temperature (25 ºC) and high temperature (237 ºC). The tensile specimen dimensions were as shown in Figure 2. Three specimens were tested for each condition.

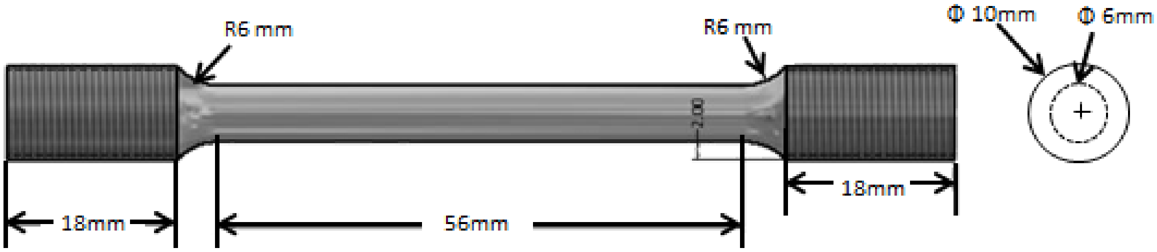

Figure 2: Tensile test specimen dimensions.

Microstructural characterization was performed on specimens obtained from tensile specimens after testing. Metallography involved polishing specimens to a 0.05µm OPS finish using standard grinding and polishing procedures. Scanning Electron Microscopy (SEM) was conducted using a Carl Zeiss LEO 1525 Field Emission Gun SEM at an accelerating voltage of 20 kV, a beam current of 10 µA and a working distance of 15 mm.

3. RESULTS AND DISCUSSION

3.1 Microstructure

The base alloy 356 had an unmodified microstructure with irregular eutectic Si particles and a small number intermetallics as shown in Figure 3a. The microstructures of the modified alloy had a larger proportion of intermetallics as shown in Figure 3. The Si particles in the microstructure of the alloy were not fully modified despite the addition of Sr. The addition of Zr, V, and Cu however caused an increased amount of intermetallics.

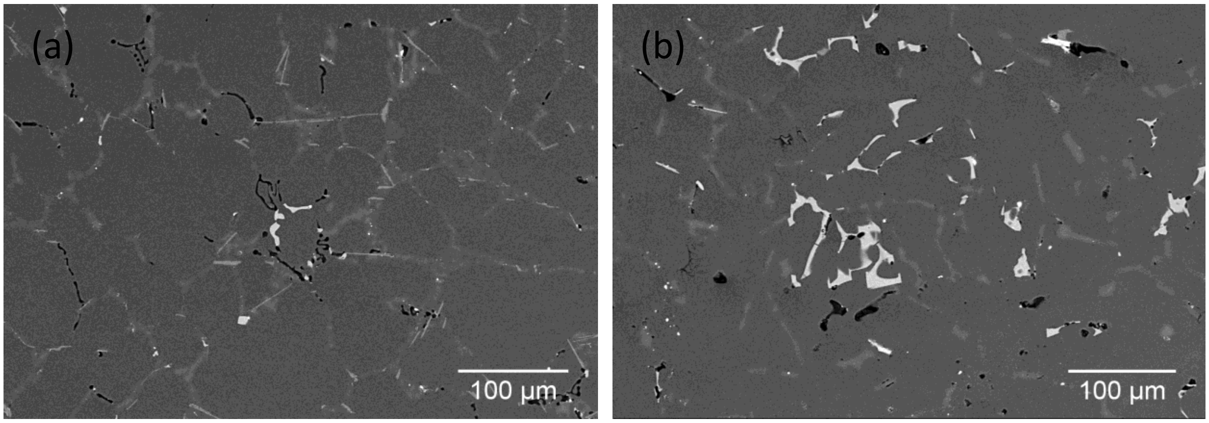

Figure 3: Microstructure of (a) the secondary 356 alloy and (b) the modified 356+0.5Cu+X alloy.

3.2 Tensile Properties

The results obtained from room temperature and high temperature (237°C) tensile tests are shown in Figure 4. The tensile properties obtained from the results are shown in Table 2.

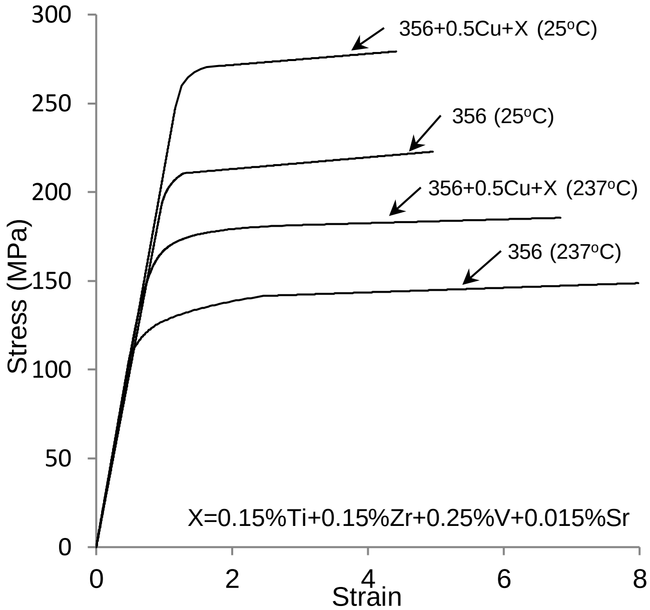

Figure 4: Tensile test results of the secondary 356 base alloy and the modified 356+0.5Cu+X alloy.

Table 2: Room and high (237°C) temperature tensile properties of the investigated alloys.

	Tensile property	**356**	**356+0.5Cu+X**	**Percent increase**
Room Temperature (25°C)	UTS (MPa)	224	279.3	24.7
	YS(MPa)	210	268	27.6
	%Elongation	5	4.4	-12
High Temperature (237°C)	UTS (MPa)	149	186	24.8
	YS(MPa)	122	167	36.9
	%Elongation	8	6.8	-15

As shown in Figure 4 and Table 2, the base alloy (alloy 356) has a room temperature ultimate tensile strength (UTS) of 224 MPa and a 0.2% proof stress or yield strength (YS) of 210 MPa. The addition of Ti, Sr, Cu and transition elements Zr and V improves the UTS to 279.3 MPa and the YS to 268 MPa. This shows a substantial increase of 24.7% and 27.6% for UTS and YS respectively. However, this increase in strength is accompanied by a 12% decrease in percent elongation from 5% to 4.4%.

Figure 4 and Table 2 also show that the base alloy (alloy 356) has a high temperature (237ºC) ultimate tensile strength of 149 MPa and a yield strength of 122 MPa. The modified alloy has an improved UTS of 186 MPa and a YS of 167 MPa. This shows a substantial increase of 24.8% and 36.9% for UTS and YS respectively. This increase in strength is also accompanied by a 15% decrease in percent elongation from 8% to 6.8%.

The improvement in room temperature UTS and YS can mainly be attributed to the modification of the microstructure of base alloy 356, solid solution strengthening due to a higher amount of dissolved solutes and the presence of strengthening precipitates such as trialuminide precipitates [1]–[4], [11], [14]–[18]. These micro-sized trialuminides are distributed in the aluminium matrix and they effectively impeded dislocations movement during the tensile deformation. These phases are stable at high temperature and can be attributed to the substantial increase in yield strength at 237ºC of 36.9% [1][3], [4], [11], [28].

The ductility of the alloy was observed to generally decrease with element addition. This is attributed to the increased amount of coarse brittle intermetallic phases. The pronounced brittle failure of the modified alloy as opposed to the base alloy is illustrated in Figure 5 that shows SEM images of the fracture surfaces of failed tensile specimens for the base alloy (Fig 5a and 5c) and modified alloy (Fig 5b and 5d) at both room temperature and high temperature. It is clear that the base alloy shows a significant dimpled fracture surfaces at both room temperature (Fig 5a) and at high temperature (Fig 5c). The modified alloy however shows a significant amount of cleavage fracture at both room temperature (Fig 5b) and high temperature (Fig 5d).

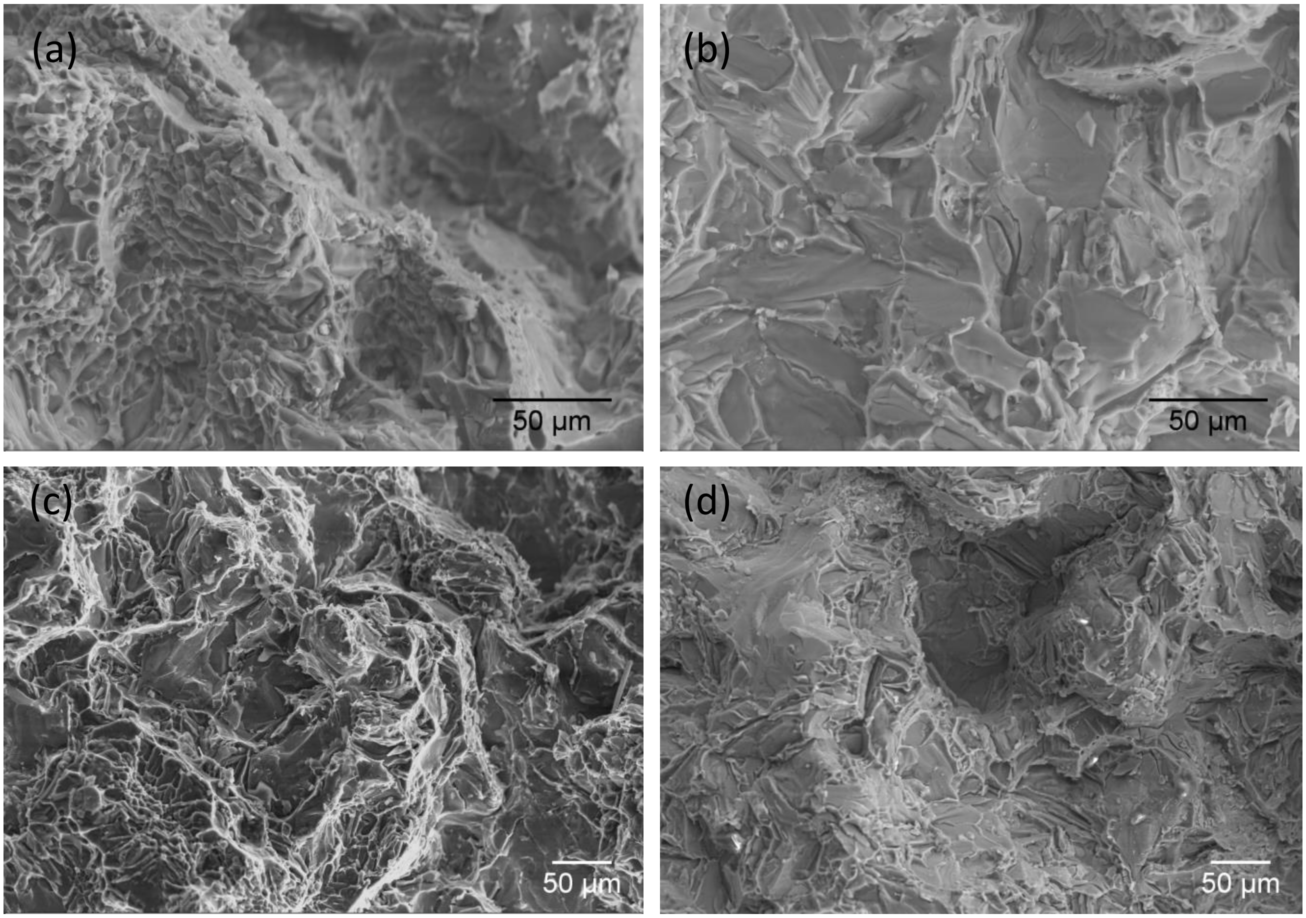

Figure 5: SEM images of the fracture surfaces of failed tensile specimens for the base alloy at room temperature (Fig 5a) and high temperature (Fig 5c) and the modified alloy at room temperature (Fig 5b) and high temperature (Fig 5d).

4. CONCLUSION

This work has demonstrated the effect of combined addition of Ti, Zr, V, CR and Cu on the microstructure and tensile properties of secondary 356 Al-Si alloys.

a. The microstructure of base alloy 356 was unmodified with irregular eutectic Si particles and a small number of intermetallics while that of 356+0.5Cu+X had larger intermetallics.
b. The values of UTS and YS at both room and high temperatures (237^{o}C) improved with the addition of Ti, Sr, Cu and transition elements Zr and V. At room temperature, there was a 24.7% and 27.5% increase in UTS and YT respectively while at high temperature (237^{o}C), the UTS and YT increased by 24.8% and 36.9% respectively. These tri-

aluminide precipitates formed are stable at high temperature (237^{o}C) and can explain the substantial increase in YT at 237^{o}C of 36.9%.

c. The decrease in percent elongation by 12% and 15% at room and high temperatures respectively can be attributed to the increased amount of course brittle intermetallic phases.
d. This work has demonstrated that secondary Al-Si alloys with minor transition element adjustment possesses better tensile properties at high temperatures and thus can re-designed to withstand the harsh operating conditions in the automotive engine.
e. Further research work should be conducted to investigate the fatigue crack behaviour of the secondary 356 alloy with transition element additions at elevated temperatures where the engine components are subjected to thermomechanical fatigue.

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