AGE HARDENING RESPONSE OF AC2B ALUMINIUM ALLOY MODIFIED WITH 0.1 wt. % Sn

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ABSTRACT

The use of aluminium alloys for automotive purpose is increasing in the last two decades, due to their light weight and corrosion resistance. One type of aluminium alloys widely used in automotive is AC2B (Al-7Si-2.8Cu) as casting products. Enhancement of mechanical properties of this alloy may be achieved through addition of alloying elements and heat treatment processes. This paper discusses the age hardening response of AC2B alloy minoralloyed with 0.1 wt. % of Sn. Tensile and hardness tests were conducted to investigate the mechanical properties of the as-cast alloys, while observation on the microstructure of the materials was carried out by using light microscopy and SEM (scanning electron microscope) equipped with EDS (energy dispersive spectroscopy).

Research results show that the addition of Sn for 0.1 wt. % is effective in increasing the age hardening response of AC2B alloy. A considerable amount of Sn was detected in association of Al_2Cu particles, which indicates facilitation of this phase by Sn, which is responsible to the increased age hardening response. Modified alloys which were cast in metal mould possess higher mechanical properties than that cast in sand mould, and this was preserved during ageing.

Keywords: AC2B, Al-Si-Cu, minoralloying, ageing, Al_2Cu

INTRODUCTION

One foundry alloy that is popular for use in automotive application is AC2B aluminium alloy, due to its excellent castability and mechanical properties. Its excellent corrosion resistance and low costs of recycling are also important considerations from an environmental point of view [1]. Aluminium alloy AC2B is essentially a hypoeutectic Al-Si alloy with two main solidification stages, formation of aluminium rich (Al) dendrites followed by development of two-phase (Al-Si) eutectic. However, the presence of additional alloying elements such as Mg and Cu, as well as of impurities such as Fe and Mn, leads to a more complex solidification sequence. Accordingly, the as-cast microstructure of AC2B alloy presents many intermetallic phases in addition to the eutectic structure. Therefore, alloying elements possess profound impact on the properties of AC2B alloy [2].

Addition of Cu to eutectic Al-Si alloys leads to a slight increase in the alloy fluidity, and a depression in the Si eutectic temperature of ~1.8 ^{o}C for every 1 wt. % Cu added. Also, some of the mechanical properties obviously benefit from the addition of Cu as an alloying element (such as yield dan tensile strength) [2]. Copper forms an intermetallic phase with Al that precipitates during solidification either as block-like Al_2Cu or in eutectic form as $(Al+Al_2Cu)$.

Another critical alloying element for AC2B alloys is iron (Fe). During solidification, it forms several intermetallic compounds. Among these, the formation of hard brittle plates of the *ß*-Al_5FeSi phase is particularly deleterious to the alloy mechanical properties [3]. This intermetallic phase also acts as nucleants for the Al_2Cu phase [4]. The formation of this Fe-containing intermetallic is also found to be responsible for the occurrence of soldering of aluminium melts in die-casting processes [5]. Magnesium (Mg) is found to considerably enhances the alloy response to artificial ageing, which is believed to be due to the formation of coarse particles of $Al_5Mg_8Si_6Cu_2$ [6].

Innovation in increasing the strength of aluminium alloys is conducted by addition of minor amount of alloying elements, or so-called as minoralloying. This is found to promote precipitation of strengthening phases within the alloys and has been widely studied for Al-Cu system. Minoralloying of Al-Cu alloys with Cd, Sn and In are known to have a finer dispersion of θ' (Al_2Cu) and exhibit an increased hardening response [7-10]. Various mechanisms have been proposed to account for this effect, i.e., one-dimensional atom probe (1DAP) experiments on an Al-1.7Cu-0.01Sn (at. %) alloy have shown that θ' nucleation is preceded by clustering of Sn atoms and the precipitation of β-Sn. The fine and uniform dispersion of θ' which follows occurs such that the incoherent rim of the precipitates is associated with Sn atoms [11]. Furthermore, Kanno *et al.* [12] have observed In particles in Al-Cu-In alloys and Nie *et al.* [13] as well as Sofyan *et al.* [14-15] have recently discussed the enhanced precipitation of θ' in Al-Cu-Sn/Cd alloys in terms of cluster-assisted nucleation. However, no study has been conducted on the effects of Sn on more complex alloys, such as AC2B alloys.

This work studied AC2B alloy added with 0.1 wt. % Sn in as-cast and as-heat treated condition. The age hardening response of the Sn-added AC2B was followed by hardness testing while microstructural evolution was observed by using SEM (scanning electron microscope) and light microscopy. Effect of mould materials was also studied.

EXPERIMENTAL METHOD

The base AC2B alloys were cast in a 300 kg industrial induction furnace ~ 300 kg. Gas buble floatation (GBF) was conducted to remove trapped hydrogen in the molten metal, by purging argon for around 10 – 15 minutes. Before pouring at 720 ± 5°C, 0.1 wt. % of Sn is charged into the molten metal by using plunger and then stirred. Alloys were cast into two different moulds, metal and resin-coated sand (RCS) mould.

Tensile test on the as-cast products is conducted in accordance with JIS Z 2201 standard, in a Shimadzu universal testing machine, with strain rate of 0.04 mm/s and loading capacity of 200 kg. Samples for tensile test were produced by casting into shaped metal moulds. For hardness testing and microanalysis, samples of alloy were cut into 10 x 10 mm blocks. After solution treatment at 505 ^{o}C for 1 h and water quenching, ageing was conducted at 30, 150, 175 and 200 ^{o}C. The age hardening response was monitored by Hoytom Brinnel hardness measurements using a 31.25 -kg load and a 2.5 mm diameter- steel ball indentor. Five indentations were measured from each sample. The evolution of microstructure was followed by means of a light microscope and LEO 420 Scanning Electron Microscope (SEM). Samples for microanalysis were prepared by etching with 0.5 % Hidrogen Fluoride.

RESULTS AND DISCUSSION

As-Cast Characteristics

Table 1 shows the composition of 0.1 wt. % Sn – added alloy in comparison with the standard composition of the base AC2B alloy. From Table 1 it is revealed that Si content of the studied alloy is slightly above the standard. On the other hand, slightly lower Cu content was detected. However, this does not seem to lead to significant effect to the properties of the alloys, since the composition remains in hypoeutectic range. Other elements are within the allowable range of composition.

Tabel 1. Comparison between composition of 0.1 % Sn – added alloy and that of standard AC2B alloy.

Element	Composition of 0.1 wt. % Sn-added alloy (wt. %)	Standard composition for AC2B alloy[16] (wt. %)
Si	7.05	5.0 – 7.0
Cu	2.85	3.0 – 4.0
Mg	0.10	0.1 max
Fe	0.41	1.0 max
Zn	0.48	1.0 max
Mn	0.16	0.5 max
Ti	0.02	0.25 max
Ni	0.02	0.35 max
Sn	0.1	0.5 max
Al	balance	balance

Mechanical properties of as-cast 0.1 % Sn – added alloy is tabulated in Table 2, which are compared to those of AC2B [16]. It reveals that the 0.1 wt. % Sn modified alloy possesses lower tensile and yield strength, by both ~ 10 %, in comparison with the standard AC2B alloy. The hardness is also lower than that of the standard alloy. Although the content of Si is slight higher and the content of Cu is slightly lower than standard, it seems to not be the cause of the discrepancy in strength. It is more likely to be due to differences in casting process parameters and condition. For example, differences in fluxing, degassing process, melting and pouring temperature.

Table 2. Mechanical properties of cast alloys and comparison with standard AC2B.

Mechanical Properties	0.1 % Sn added alloy	AC2B [16]
Tensile strength	210 MPa	235 MPa
Yield strength	116 MPa	130 MPa
Elongation	3.0 %	2.5 %
Hardness (metal mould)	67 BHN	85 BHN
Hardness (sand mould)	62 BHN	70 BHN

Figure 1 shows as-cast microstructure of 0.1 wt. % Sn - added AC2B alloys, both in metal and sand moulds. Alloy which was cast in metal mould possesses finer dendritic structure than that in sand mould, so that leads to higher hardness of metal mould alloy, as shown in Table 2. The finer structure is due to faster heat transfer in metal mould. The microstructure of this as-cast alloy is in good comparison with previous reports elsewhere. The as-cast microstructure consists of Al-rich dendrites with interdendritic structures, which are thought to be Al_2Cu, Al_5FeSi or Si-rich crystals [17].

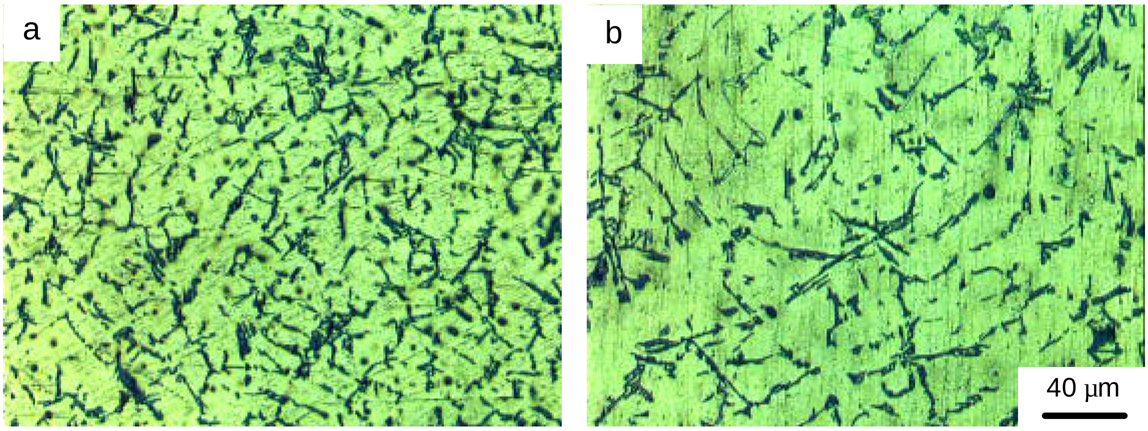
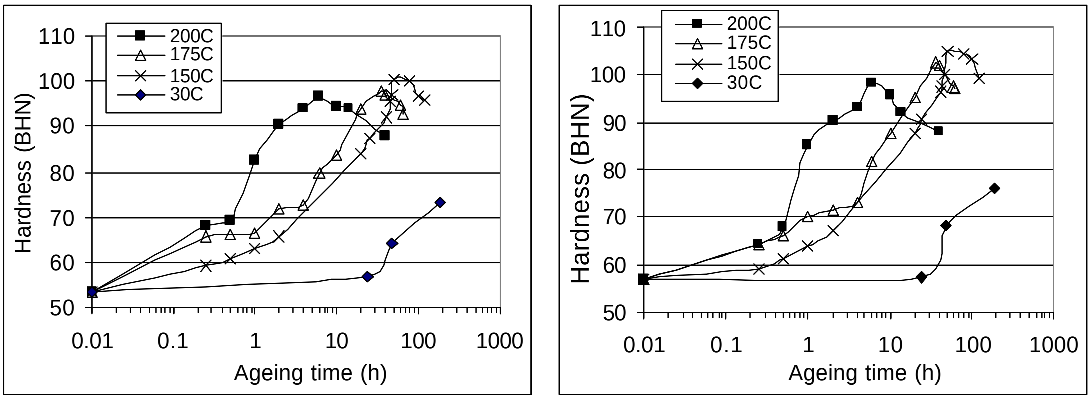


Figure 1. As-cast microstructure of 0.1 wt. % Sn – added AC2B alloys cast in (a) metal mould, and (b) sand mould.



(a) (b)

Figure 2. Hardness response of 0.1 wt. % Sn – added alloy cast in (a) sand mould, and (b) metal mould, upon ageing at 30, 150, 175 and 200 ^{o}C.

Age Hardening Response

Figure 2 (a) and (b) provides age-hardening curves of 0.1 % Sn-modified alloy during ageing at 30 °C (natural ageing), 150 °C, 175 °C dan 200 °C (artificial ageing). An incubation period for ~ 20 h was detected in natural ageing, which then followed by an increase to peak hardness. While artificially aged alloys show increase in hardness once the ageing starts. It is clearly revealed that the highest peak hardness was achieved when the alloy was aged at 150 ^{o}C for 50 h, in which the hardness increases by 26 % compared to the as-cast condition. With the increase in ageing temperature, the peak hardness decreases but shorter time is needed to reach the peak hardness. This phenomenon is similar to both alloys cast in metal and sand molds. The shorter time needed to reach peak hardness at higher ageing temperature is due to faster diffusion, which leads to higher growth rate of strengthening precipitates. On the other hand, at lower ageing temperature, precipitate nucleation rate is higher and the precipitate growth rate is lower. Therefore, finer but denser distribution of precipitates is expected to occur. This gives rise to higher peak hardness due to effective impediment of dislocation movement by the precipitates. However, at low temperature, diffusion rate is slower so that need longer time to reach the peak hardness.

The difference in hardness between the metal and sand mould alloys is ± 5 BHN, throughout the ageing process. This is the same with the difference in as-cast hardness, which indicates that the difference in characteristics due to type of mould is preserved during ageing.

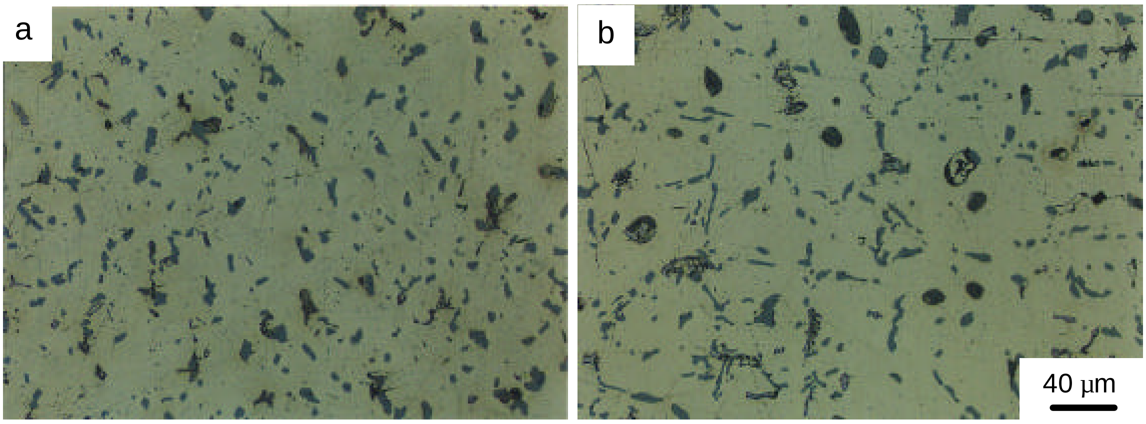


Figure 3. Microstructures of 0.1 wt. % Sn – added AC2B alloys upon natural ageing for 8 days (192 h): (a) metal mould, and (b) sand mould.

Microstructural Analysis

Microstructures of modified alloys upon natural ageing for 8 days (192 h) are presented in Figure 3. It reveals that the interdendritic structure of the alloys seems to slightly dissolves in the matrix, in comparison with the as-cast ones. The dissolution occurs during solution treatment at 505 ^{o}C. Since ageing at room temperature for 192 h remains in incubation period, where no significant increase in hardness was detected (see Figure 2), it is much expected that no change in microstructure might occur at this stage in comparison with the as-quenched condition. It is also apparent that dendritic arm spacing in both alloys remains the same with that in as-cast state, which explains the preservation of hardness during ageing.

A series of microstructural evolution of AC2B alloys added with 0.1 wt. % Sn, for both sand and metal moulds, during ageing at 150 ^{o}C, is presented in Figure 4. All micrographs have the same magnification as shown by the scale bar. It is confirmed that alloys cast in metal moulds have relatively finer dendritic structure that that of the sand mould, although the difference is not as clear as those in the as-cast microstructures (Figure 1). Dissolution of interdendritic structure is again clearly observed, where it looks more spheroidized. No spherical Sn particles were detected to form in all microstructure, which is different with the previous report in higher Sn content, 2.0 wt. % [18]. The absence of these elementals particles may indicate that all Sn atoms occupy sites in aluminium matrix due to its low concentration. Fine and nanoscale precipitates were not detected here due to the limitation of light microscopy.

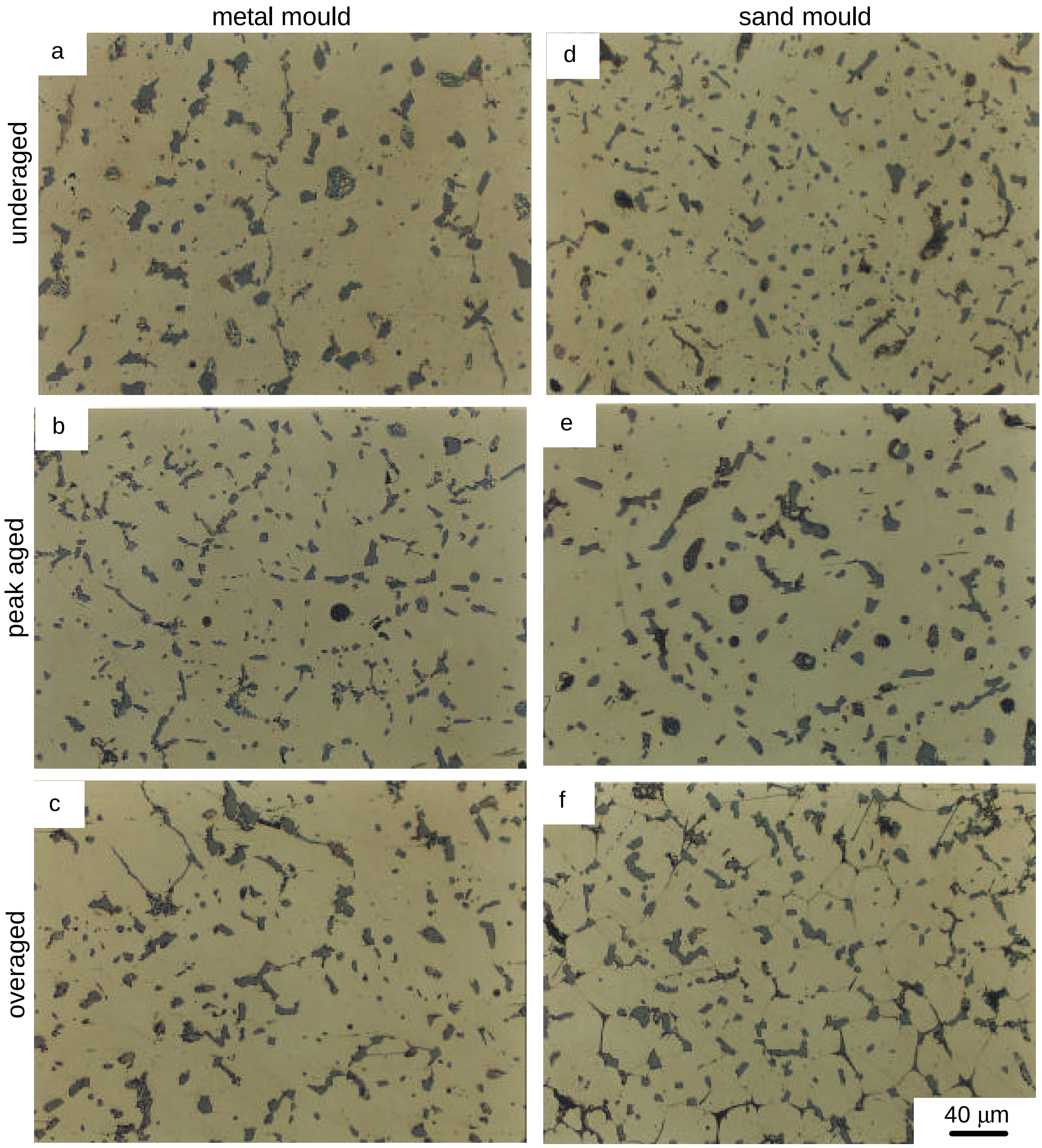


Figure 4. Evolution of microstructure of 0.1 % Sn - modified AC2B alloys cast in (a – c) metal mould, and (d – f) sand mould, during ageing at 150 ^{o}C.

To retrieve the presence of Sn, microanalysis by using EDS/SEM was conducted. Figure 5 shows a SEM micrograph of a 0.1 wt. % Sn - modified AC2B alloy cast in sand mould and over-aged at 200 ^{o}C. Microanalysis result from each position in Figure 5 is presented in Table 3. It is noteworthy that at position 1, a considerable amount of Sn together with Mg is detected. The Mg content of the alloy is only 0.1 wt. % and the solubility of Mg in Al is 17.4 wt. % at 450^{o} [19]. The Mg-rich particle may be ? Mg_5Al_8 , Al_3Mg_2 as indicated by possible intermetallic in Al-Mg system. Formation of this intermetallic seems to be induced by availability of vacancies that assist diffusion of solute to form such phase. Clustering of vacancy may be promoted by the presence of Sn, which possesses large size that cause strain of aluminium lattice. Presence of Sn of 74.2 wt. % at this position supports this notion. This phenomenon was similar to that occurs in Al-Cu system [11]. The Sn-Mg rich position is also associated with Al_2Cu (position 2), which indicates that Sn play an important role in formation of this phase. This is confirmed by the fact that the peak hardness of this alloy is higher that that of the Sn-free AC2B [16]. Other major interdendritic structures found in this alloy are primary Si crystals and a-Al-Fe-Mn-Si. The SEM micrograph reveals no elemental Sn particles independently forms in the matrix, which confirms that addition of Sn for 0.1 wt. % is an adequate amount to allow the Sn atoms occupy matrix lattice without formation of soft elemental Sn particles that have detrimental effects on the properties.

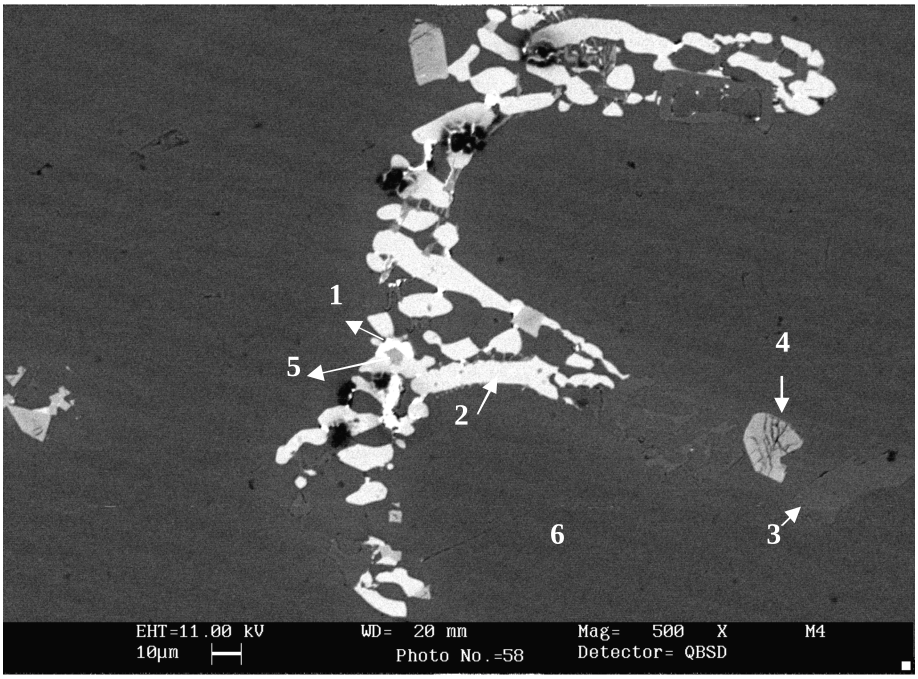


Figure 6. SEM micrograph of a 0.1 wt. % Sn - added AC2B alloy over-aged at 200 ^oC.

Table 3. Microanalysis result on positions shown in Figure 5.

No	**Content (wt. %)**							**Colour**	**Possible phase**
	Al	**Si**	**Cu**	**Fe**	**Mn**	**Sn**	**Mg**		
1	16.8	-	-	-	-	74.2	9.0	Bright white	? Mg_5Al_8 , Al_3Mg_2
2	85.6	1.7	12.7	-	-	-	-	White	Al_2Cu
3	0.6	99.42	-	-	-	-	-	Grey	Silicon crystal
4	74.8	10.05	1.2	8.8	4.0	-	-	Bright grey	a Al-Fe-Mn-Si
5	73.9	9.5	1.3	12.7	1.6	-	-	Dark grey	a Al-Fe-Mn-Si
6	97.4	2.2	0.4	-	-	-	-	Matrix	Al matrix

CONCLUSIONS

1. Addition of 0.1 % Sn is effective in improving age hardening of AC2B alloy. This may be due to the facilitation of second phase particles, such as Al_2Cu, due to its high binding energy with vacancy, which may enhance diffusion process.
2. Alloys cast in metal moulds seem to have higher mechanical properties than that in sand mold, due to faster heat transfer which then lead to finer dendritic structures.

3. Differences in hardness in as-cast condition are preserved during ageing, which indicates that ageing leads to no change in the dendritic structure.
4. Dissolution of interdendritic structure during solution treatment seems to be occurred.
5. The highest hardness of 0.1 wt. % Sn – added alloy was achieved by ageing at 150 ^oC for 50 h, in which the hardness increases by 26 % compared to the as-cast condition.
6. Microstructure of Sn-modified AC2B alloys consists of Al dendrites with interdendritic particles, such as: Al_2Cu, primary Si crystal, α-Al-Fe-Mn-Si and Al-Si eutectic. Some Al_2Cu particles are associated with Sn, which may indicate that Sn plays a role in the formation of this structure.

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