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AS-CAST PROPERTIES AND AGE HARDENING RESPONSE OF AA319 ALUMINIUM ALLOYS WITH VARIOUS Sn CONTENT

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ABSTRACT

One type of cast aluminium alloys widely used in automotive is AA319 (Al-6Si-2.8Cu). The properties of this type of alloy are widely known to be sensitive to alloying element and may be enhanced through heat treatment processes. This paper discusses the as-cast characteristics and age hardening response of AA319 cast alloy minoralloyed with various amount of Sn, 0.1 – 2 wt. %. Tensile and hardness were conducted as well as observation on the microstructure of the materials in as-cast and as-aged condition by using light microscopy and SEM (scanning electron microscope) equipped with EDS (energy dispersive spectroscopy).

Research results showed that the as-cast hardness of AA319 alloys increased with addition of Sn for 0.1 wt. % and then decreased with further addition of Sn. Similar trend was found for as-quenched hardness and ageing response at 90, 150 and 200 ^{o}C. Addition of more than 0.1 wt. % Sn led to segregation of Sn, which may indicate that Sn precipitated out of the matrix, so that was not available in facilitating precipitation processes within the matrix. Modified alloys which were cast in metal mould possessed higher mechanical properties than that cast in sand mould, and this was preserved during ageing.

Keywords: AA319, Al-Si-Cu, minoralloying, ageing, Al_2Cu

1. INTRODUCTION

One foundry alloy that is popular for use in automotive application is AA319 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. Aluminium alloy AA319 is essentially a hypoeutectic Al-Si alloy with two main solidification stages, formation of aluminium rich 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 AA319 alloy presents many intermetallic phases in addition to the eutectic structure. Therefore, alloying elements possess profound impact on the properties of AA319 alloy [1].

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. Copper forms an intermetallic phase with Al that precipitates during solidification either as block-like Al_2Cu or in eutectic form as $(Al+Al_2Cu)$ [1].

Another critical alloying element for AA319 alloys is iron (Fe). During solidification, it forms several intermetallic compounds. Among these, the formation of hard brittle plates of the β-Al_5FeSi phase is particularly deleterious to the alloy mechanical properties [2]. This intermetallic phase also acts as nucleants for the Al_2Cu phase [3]. 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 [4]. 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 $Al_5Mg_8Si_6Cu_2$ [5].

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 [6-8]. 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 [8]. Furthermore, Kanno *et al*. [9] have observed In particles in Al-Cu-In alloys and Nie *et al*. [10] as well as Sofyan *et al.* [11-12] 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 AA319 alloys.

This work studied AA319 alloy added with various Sn content in as-cast and as-heat treated condition. The age hardening response of the Sn-added AA319 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.

2. EXPERIMENTAL METHOD

Four Sn-modified alloys were cast by using commercial AA319 as the base alloy and their nominal composition is presented in Table 1. These alloys were melted in an industrial furnace and gas bubble floatation process by using argon was used to remove trapped air from the molten metal. Pure Sn ingot was added into the molten metal at 710 ^{o}C before pouring. Molten metal was then cast into two different moulds, metal dan resin-coated sand moulds. Therefore, it is expected that heat transfer in both moulds is different.

Table 1. Nominal composition (wt. %) of alloys in this study

Alloys	Si	Cu	Mg	Fe	Mn	Sn	Al
319	6.0	2.8	0.15	0.44	0.14	-	rem
319 + 0.1 % Sn	6.0	2.8	0.15	0.43	0.12	0.1	rem
319 + 0.5 % Sn	6.0	2.8	0.15	0.38	0.10	0.5	rem
319 + 1 % Sn	6.0	2.8	0.15	0.41	0.14	1.2	Rem
319 + 2 % Sn	6.0	2.8	0.15	0.44	0.14	2.0	Rem

Samples of each alloy were cut into 10 x 10 mm blocks for hardness testing and microanalysis of the as-cast condition.

Similar samples were solution treated at 505 ^{o}C for 1 h in a salt bath and subsequently quenched into cold water at 15 ^{o}C. Ageing was conducted at 90, 150 and 200 ^{o}C in a silicone oil bath. Hardening response was monitored by hardness measurements using a 5-kg load Vickers. Seven indentations were taken for each hardness measurement. The evolution of microstructure was followed by means of a light microscope and LEO 420 SEM. Samples for microstructural analysis were prepared by etching with 0.5 % Hidrogen Fluoride.

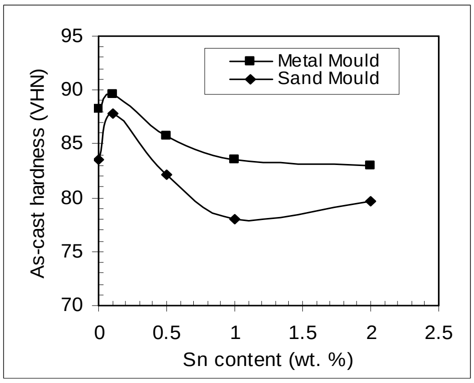

Fig. 1. Effect of Sn content and mould material on as-cast hardness of AA319 based alloys.

3. RESULTS AND DISCUSSION

3.1. As-Cast Characteristics

Fig. 1 shows the effect of Sn content on the as-cast hardness of AA319 alloys. It is apparent that addition of small amount of Sn, less than 0.1 wt %, increases the as-cast hardness of AA319 alloys but further addition results in detrimental effect. This is similar to the effects of Sn on binary Al-Cu alloys [7-12], in which addition a small amount of Sn may induce strain field within the Al matrix, due to large misfit between Sn and Al atoms. However, when more Sn is added, the atoms tend to form elemental Sn particles, since Sn is miscible in Al. Formation of these elemental Sn particles, which are soft, led to the decreases in hardness of the alloys. The trend is similar for both alloys cast in metal and sand moulds, while the latter possessed lower hardness.

Fig. 2 shows as-cast microstructures of AA319 alloys with various Sn content, both in metal and sand moulds. In general, the as-cast microstructures show dendritic structures which consist of α-aluminium matrix and interdendritic second phases, such as Al_2Cu, Al(Fe,Mn)Si and Si primary crystals [1]. All alloys cast in metal moulds possess finer dendritic structure than those cast in sand moulds. This correlates well with the facts that alloys cast in metal moulds possess higher hardness, as can be seen in Fig. 1. The finer structure is due to faster heat transfer in metal mould. Aside from the finer dendritic structures, it is also apparent that the Si primary crystals in alloys cast in metal moulds have finer structures, which indicate that heat transfer also affect the formation of this phase. The effects of Sn content to as-cast microstructures can not be revealed in the micrographs due to limited resolution of light microscope.

3.2. Age Hardening Response

Effect of Sn content on as-quenched hardness of AA319 alloys is presented in Fig. 3, and the curves are similar with that in Fig. 1, the as-cast hardness. Addition of Sn up to 0.1 wt. % Sn increased the as-quenched hardness, but with further addition of Sn, the as-quenched hardness decreased. The difference of hardness between the metal mould and the sand mould alloys was preserved upon quenching. This indicates that solution treatment did not change the dendritic structures of the alloys, rather it might dissolve some second phase particles.

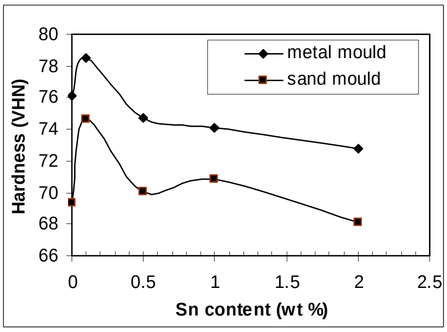

Fig. 3. Effect of Sn content and mould material on as-quenched hardness of AA319 based alloys.

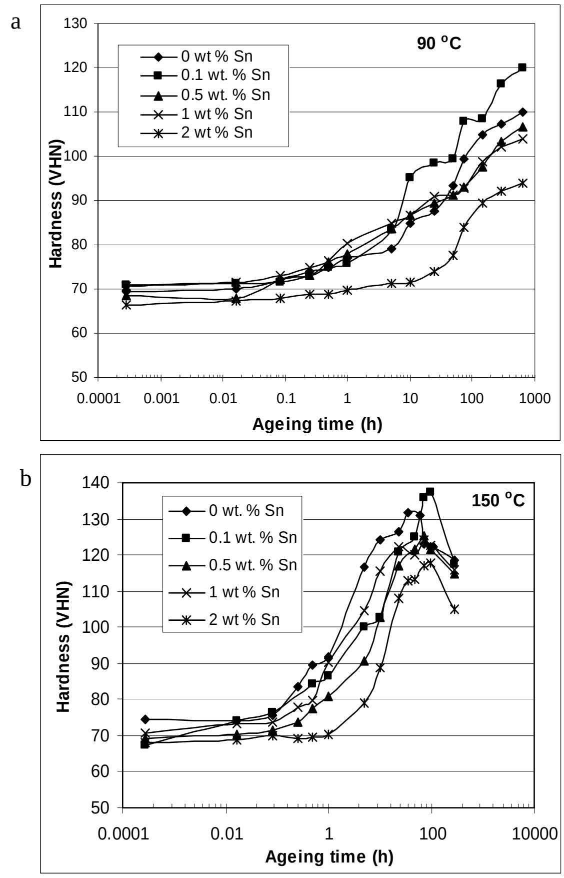

Fig. 4. Effects of Sn on ageing response of AA319 alloys at (a) 90 ^{o}C, and (b) 150 ^{o}C. All alloys were cast in sand mould.

Age hardening response of Sn-containing alloys at 90 and 150 ^{o}C is presented in Fig. 4 (a) and (b), respectively. All alloys showed an incubation period of between 10 min and 1 h. For both ageing temperatures, alloy with 0.1 wt. % Sn possessed the highest response, and the response was getting lower as the Sn content increased. The peak hardness of this alloy (containing 0.1 wt. % Sn) upon ageing at 150 ^{o}C, was 138 VHN. This was a remarkable increase, of around 156 %, in comparison to the as-cast hardness. The highest response of 0.1 wt. % Sn-containing alloy indicates that promotion of second phase precipitates is effective with this amount of Sn. Vacancies trapped by Sn during quenching are adequate to assist diffusion throughout ageing. However, addition of more Sn resulted in formation of elemental Sn particles, due to the immiscibility of Sn in aluminium, so that Sn are not available in the matrix to assist diffusion process in precipitate nucleation. The formation of Sn particles was confirmed by SEM observation, which is discussed in subheading 3.3. These results are similar to previous study in Al-Cu system, in which 0.01 at. % Sn was found to be effective in promoting formation of θ' precipitates [8].

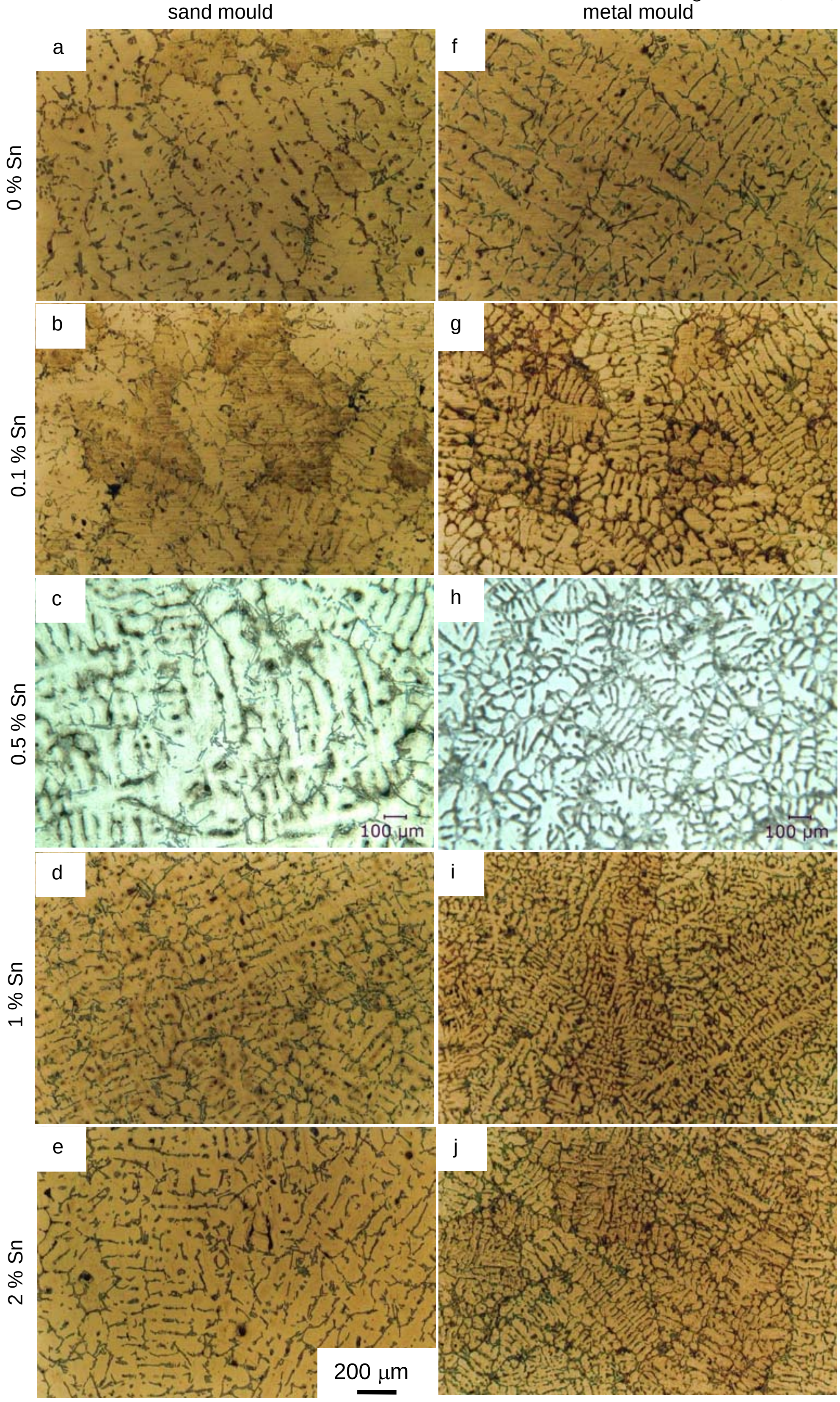

Fig. 2. As-cast microstructures of AA319 alloys containing 0 – 2 wt. % Sn, cast in (a-e) sand moulds, and (f-j) metal moulds.

It is also noteworthy that that addition of Sn increased the incubation period (Fig. 4), This may indicate that with higher amount of Sn, more vacancies are trapped by Sn, but because Sn then form elemental particles, the vacancies alone are not able to accommodate shear strain that can ease nucleation of platelike θ'

3.3. Microstructural Evolution during Ageing

Microstructural evolution of all alloys at different ageing temperatures was followed by light microscope, and an example of the result is presented in Fig. 5, for 0.5 wt. % Sn – containing AA319 alloys, during ageing at 150 ^{o}C. All micrographs have the same magnification as shown by the scale bar. No change in dendritic structure was observed during ageing. Dissolution of interdendritic particle was not apparent either. This suggests that increase in hardness during ageing is due to precipitation of nanoscale precipitates within the α matrix, which was not detected here due to the limitation of light microscopy.

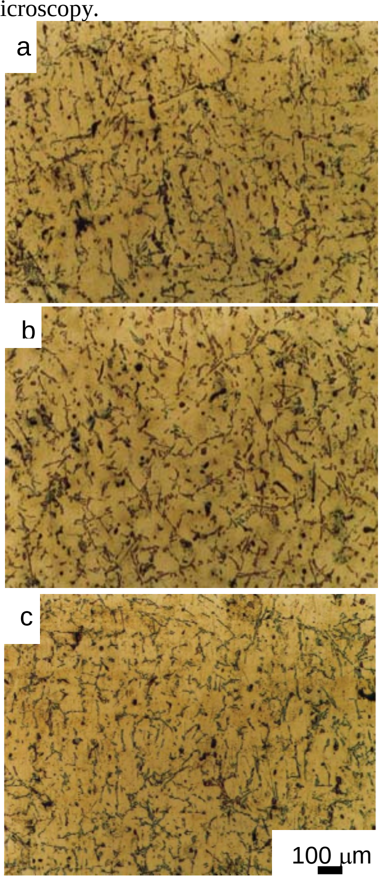

Fig. 5. Evolution of microstructure of AA319 alloy added with 0.5 wt. % Sn during ageing at 150 ^oC.

To retrieve the presence of Sn, microanalysis by using SEM/EDS was conducted. Figure 6 shows a SEM micrograph of a 0.5 wt. % Sn - modified AA319 alloy cast in sand mould and aged at 200 ^oC for 14 h. Microanalysis results from each position in Figure 6 are presented in Table 2. It is noteworthy that at position 1, a white particle containing 48.1 wt. % Sn with the diameter of ~ 2 μm, was detected in conjunction with Al_2Cu phase. The large size of Sn particles indicates that they form during solidification due to its limited solubility in aluminium. The formation of Sn elemental particles leads to its unavailability in the matrix to promote precipitation process. The presence of soft Sn particles also led to detrimental effects on the properties of the alloy. This is different with that in 0.1 wt. % Sn – containing alloy, which has no elemental Sn particles in the microstructure [13, 14]. Other major interdendritic phases form in the alloy are Al(Fe,Mn)Si and primary Si crystal.

4. CONCLUSIONS

1. As-cast hardness and ageing response of AA319 alloy increased with addition of 0.1 % Sn, but then decreased with further addition of Sn.
2. The higher the Sn content, the longer incubation period during ageing at 90 and 150 ^oC.
3. Addition of 0.1 wt. % Sn is effective in improving age hardening of AA319 alloy that may be due to the facilitation of second phase precipitates due to its high binding energy with vacancy. Further addition of Sn leads to formation of Sn elemental particles that have detrimental effects on the properties of AA319.
4. Microstructure of Sn-modified AA319 alloys consists of Al dendrites with interdendritic particles, such as: Al_2Cu, primary Si crystal, and Al(Fe,Mn)Si. Some Al_2Cu particles are found to be associated with Sn.
5. Alloys cast in metal moulds possessed higher mechanical properties than those in sand mold, due to faster heat transfer which then led to finer dendritic structures.
6. Differences in hardness in as-cast condition are preserved during ageing, which indicates that ageing leads to no change in the dendritic structure.

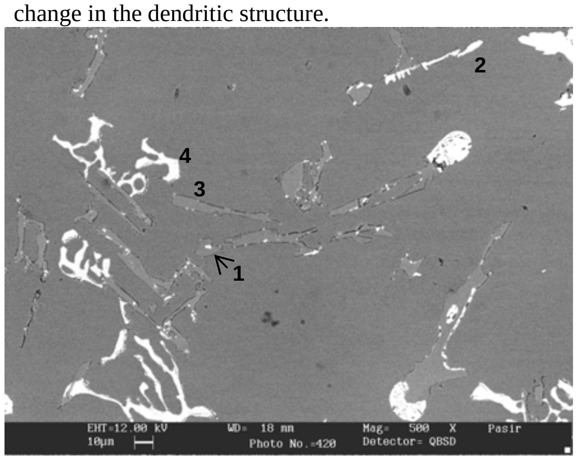

Fig. 6. SEM micrograph of a 0.5 wt. % Sn - added AA319 alloy aged at 200 ^oC for 14 h.

Table 2. Microanalysis result on positions shown in Figure 6.

No	Element (wt. %)						Possible phase
	Al	Si	Cu	Fe	Mn	Sn	
1	10.1	16.6	22.8	-	-	48.1	Al_2Cu + Sn cluster
2	48.4	13.3	13.0	19.1	5.5	-	Al(Fe,Mn)Si
3	0.6	99.4	-	-	-	-	Silicon crystal
4	46.4	14.5	11.1	22.4	5.6	-	Al(Fe,Mn)Si

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