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Multiple precipitation pathways in an Al-7Si-0.6Mg alloy fabricated by selective laser melting

Jeremy H. Rao [a,b], Yong Zhang [a,*], Kai Zhang [b,c], Aijun Huang [a,b], Chris H.J. Davies [b,c], Xinhua Wu [a,b]

[a] Department of Materials Science and Engineering, Monash University, Clayton, VIC 3800, Australia
[b] Monash Centre for Additive Manufacturing, 15-17 Normanby Road, Notting Hill, VIC 3168, Australia
[c] Department of Mechanical and Aerospace Engineering, Monash University, Clayton, VIC 3800, Australia

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ABSTRACT

The ageing responses of selective laser melted Al-7Si-0.6Mg alloy with different solid solution treatment times are investigated in this work. Silicon particles with random crystallographic orientations are the dominant precipitates at the direct aged condition. With 1 or 8 h solid solution treatment, the precipitation sequence resembles that of cast/wrought Al-Si-Mg alloys. However, the main precipitates at the peak-aged condition are different and are premature B′ (1 h) and β″ (8 h), respectively. These unusual precipitation pathways are attributed to the uniaxial strains in the Al matrix, suggesting new heat treatment procedures required for selective laser melted alloys.

Additive Manufacturing (AM), also known as 3D printing, is a process by which a complex part is fabricated layer by layer from a digital design package [1,2]. AM has the potential to conserve raw materials, and to reduce the energy consumption, part cost, and fabrication time [3]. As one of the common AM technologies, selective laser melting (SLM) is capable of processing or switching between different material systems [4,5]. SLM is now used as a cost effective method for the manufacturing of metals, such as Al-Si alloys [6,7].

Aluminium cast alloys have been attractive alternatives to some conventional steels due to their higher corrosion resistance [8]. As a typical cast alloy, A357 Al alloy (Al-7Si-0.6Mg) is suitable for light weight construction and at the same time meets the requirements of structural durability, and thus is highly demanded in a variety of automotive and aerospace engineering applications [9].

A357 Al alloy can be strengthened by precipitation hardening after solid solution treatment. The precipitation sequence can be expressed as [10–13]:

(Mg + Si) cluster/GP-I zones → β″ (Mg_5Si_6 or $Mg_5Al_2Si_4$)/GP-II zones → B′ ($Al_3Mg_9Si_7$) and β′ → β (Mg_2Si). β″ is the dominant precipitate in the peak-aged A357 alloy and forms needles along $[100]_{Al}$ [14]. B′ (also called Q phase in Cu-containing Al-Mg-Si alloys) is often observed in over-aged Al-Mg-Si alloys [15]. B′ forms laths along $[100]_{Al}$ and is slightly different from β″ in terms of cross-section morphology [12,16,17].

The rapid cooling rate during selective laser melting (up to 10^6 K/s) can result in the solute concentration higher than the equilibrium values, which is known as solute trapping [17]. In selective laser melted (SLMed) A357 alloy, the initial Si concentration in the Al matrix is 5.4 wt% and can be reduced to 0.5 wt% after 1 h solid solution treatment at 535 °C [18]. Therefore, as-SLMed A357 alloy is ready for direct artificial ageing because of the high supersaturation of Si and Mg. In this regard, it is important to understand the ageing responses of selective laser melted A357 alloy with or without solid solution treatment applied because conventional heat treatment protocols designed for cast/wrought alloys might not be suitable for additive manufactured alloys [19].

A357 Al alloy (10 mm × 10 mm × 10 mm) was fabricated by SLM and detailed information can be found in an early study [10]. The prepared samples were directly aged at 165 °C or first solid solution treated at 535 °C for 1 h (or 8 h) and then aged at 165 °C or 180 °C. The Vickers hardness was measured using a macro hardness tester with a load of 1 kg. The mean values of 5 measurements are reported. TEM characterisation was carried out on FEI Tecnai G2 T20 and FEI TITAN[3]. TEM specimens were first prepared by mechanical grinding and finally thinned by a precision ion polishing system (PIPS).

Direct ageing after SLM can effectively strengthen the alloy, as shown by the hardness curve in Fig. 1a. Even though the hardness increment is lower, the directly aged SLMed A357 has a higher peak hardness value compared to cast A357. The precipitates at the peak-aged condition are shown in Fig. 1b. Selected area electron diffraction pattern (SAED, inset in Fig. 1b) suggests these precipitates are randomly oriented Si particles. Some Si particles with Moiré fringes adopt the

* Corresponding author.
E-mail address: yong.zhang2@monash.edu (Y. Zhang).

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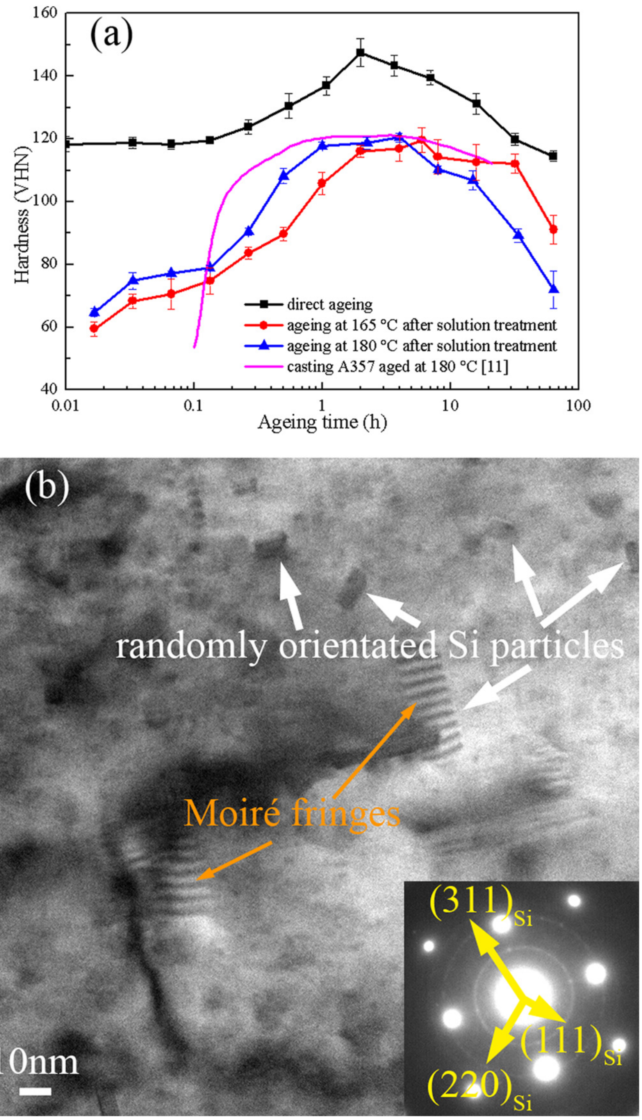

Fig. 1. (a) Hardness curves for SLMed A357 alloy together with cast A357, (b) TEM image showing randomly oriented Si particles in SLMed A357 alloy directly aged for 2 h (peak-aged condition), the inset displaying SAED pattern of this area.

common crystallographic orientation of Si precipitates in cast Al-Si alloys, while the rest have random orientations. In as-SLMed A357 samples without post heat treatment, the randomly oriented Si crystals are not observed (Fig. S1a).

The hardness curve for the SLMed A357 alloy with 1 h solid solution treatment is different from directly aged SLMed A357 but is similar to cast A357 alloy (Fig. 1a). However, according to the cross-section morphology along $[100]_{Al}$, these precipitates are not β″ at the peak-aged condition in SLMed A357 alloy with 1 h solid solution treatment. SAED pattern of these precipitates is also different from that of β″: streaks of β″ are not present (inset in Fig. 2a). High resolution images of these precipitates and the corresponding fast Fourier transformations (FFT) in Fig. 2c suggest these precipitates are B′. Although B′ (or Q) is generally observed in overaged cast Al-Si-Mg-(Cu) alloy [11,15,16], they are formed at the peak-aged condition in SLMed Al-Si-Mg alloy. β″ also exists at this condition, but its number density is much lower than B′ (Fig. 2b). An interesting question arises now: which precipitate forms first during artificial ageing in SLMed A357, β″ or B′?

Typical precipitates in under-aged sample with 1 h solid solution treatment are shown in Fig. 3. β″ is the dominated precipitate, and B′ is not found in grain interior. SAED pattern also shows streaks caused by reflections from β″. Therefore, B′ forms after β″ in the SLMed A357 with 1 h solid solution treatment, which is the same precipitation sequence for cast counterparts exhibited above. However, with a comparable peak ageing time, instead of β″, B′ is the main strengthening precipitate in the SLMed alloy as discussed above, meaning solute diffusion and even precipitate nucleation is much easier in the SLMed alloy compared to the cast counterparts. Furthermore, precipitation hardening mainly replies on the number density of precipitates and the ability of precipitates in hindering dislocation movement. Since B′ misfits more with the Al matrix than β″, B′ is predicted to be more effective in resisting dislocation motion and hardening the alloy. Therefore, in the SLMed A357 with 1 h solid solution treatment, since the number density of B′ at the peak-aged condition is comparable to β″ at the under-aged condition (Figs. 2b and 3a), peak hardness is not reached until B′ is copiously formed.

SLMed A357 alloy with or without solid solution treatment shows different ageing responses compared to cast A357. The precipitation of randomly oriented Si particles in directly aged SLMed A357 can be partially explained by the much higher supersaturation of Si element. The maximum Si concentration in cast A357 alloy with solid solution treatment is set by the maximum equilibrium Si solubility in Al (1.6 wt% [20]). However, in SLMed A357 without solid solution treatment, the high Si concentration of 5.4 wt% [18] gives Si a higher driving force to cluster and precipitate out than Mg (0.6 wt%). Therefore, it is expected that Si atoms form Si particles much more quickly, while the clustering of Mg is too slow to catch up that of Si due to much lower supersaturated Mg element, making the formation of (Mg + Si) clusters and β″ impossible. On the other hand, a comparably high Si supersaturated content (6 wt% Si, achieved by high pressure compression) in a cast Al-Si alloy does not results in random orientations but still creates a certain crystallographic orientation for Si particles with the Al matrix [21].

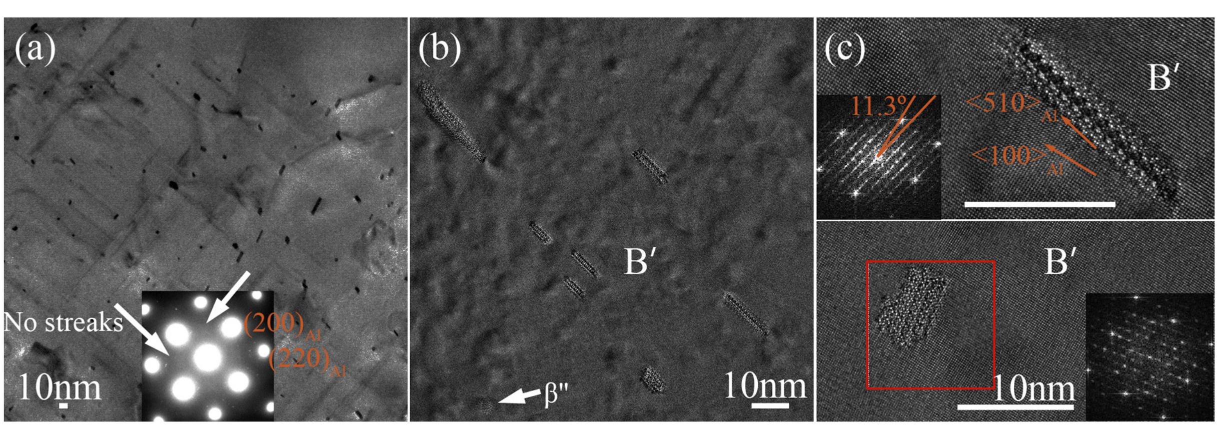

Fig. 2. B′ precipitates in SLMed A357 alloy aged for 6 h after 1 h solid solution treatment (peak-aged condition). The Al grain was titled along $\langle 001 \rangle_{Al}$. The insets are SAED or FFT of the TEM images. Red rectangles highlight the region of FFT. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)