Nanoscale characterization of β" and Cu containing precipitates in a Cu added Al-Mg-Si alloy

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Age-hardenable Al-Mg-Si alloys have superior mechanical properties and commonly used for building components and automotive parts. The strength of alloys are strongly dependent on the microstructure of precipitates, in which their sequences are generally accepted as following: supersaturated solid solution (SSSS) → G.P. zone → β"→ U1, U2, B', β' → β[1]. It is also reported that the precipitation sequences are altered by addition of Cu as: SSSS → G.P. zones → β", L, S, C, QP, QC → Q', β' → Q[2]. In this study, atomically-resolved scanning transmission electron microscopy (STEM) was carried out to reveal the microstructures of the precipitates and to clarify the precipitation sequences of Cu added Al-Mg-Si alloy at atomic scale precision.

6016 Al alloy used for this study was solutionized at 823 K for 0.5 h, followed by water quenching, and aged at 453 K for 0.5 h ~ 7 h. The specimens for STEM observation were prepared by twin-jet electro-polishing used with an electrolyte solution composed of 10 vol% of $HClO_4$ and 90 vol% of C_2H_5OH. STEM studies were carried out via JEOL JEM-ARM 200F equipped with a cold field-emission gun and a spherical aberration corrector for electron probe, operated at 60 kV and 120 kV.

Figure 1(a) shows atomically-resolved HAADF-STEM image of a precipitate in the alloy aged for 0.5 h. Although the aging period of 0.5 h was shorter than the peak aging period of 2.0 h, sub-unit cells of the β" phase were recognized clearly in the precipitate, as indicated in figure 1(b). In addition, Cu containing structures with three-fold symmetry were also observed in the same precipitate. β" sub-unit cells were present around the Cu containing structures. Some of β" sub-unit cells were found disordered in the precipitate. This results suggested that the precipitate consisted of the mixture of β" sub-unit cell and Cu containing structure, and the formation of the Cu containing structures would probably be a cause of the formation of the disordered β" sub-unit cells.

Figure 2 (a-e) show chemical map of the atomic columns in the β" precipitate. In the β" precipitate, Al atomswere still present in the structure, with $Mg_{5-x}Al_{x+y}Si_{6-y}$ of the composition. Cu atoms were also found present in the Al site of the precipitate, which suggests that Cu would be replaced with Al atom, not only in the Al matrix but also in the β" precipitate.

In summary, the precipitates in the Cu added Al-Mg-Si alloy aged for 0.5 h are formed with β" and Cu containing structure. The composition of β" was expected as Mg, Al and Si, rather than the previously reported Mg_5Si_6, and Cu could be replaced with Al in β".

[1] C. D. Marioara, et al. *Philos. Mag.*, **87** (2007) 3385-3413

[2] T. Saito, et al. *Philos. Mag.*, **94** (2014) 520-531

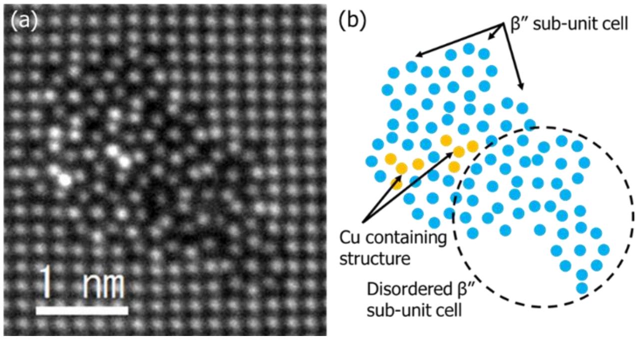

Figure 1. (a) Atomically resolved HAADF-STEM image of the precipitate in the Al-Mg-Si alloy aged for 0.5 h. (b) Schematic diagram of the precipitate shown in Fig. 1(a).

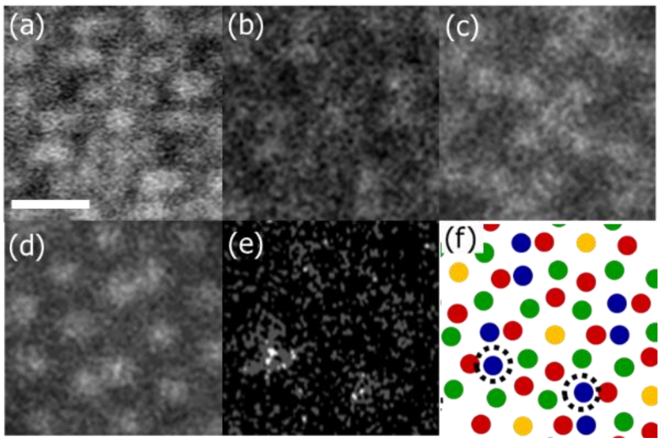

Figure 2. (a) Atomically resolved HAADF-STEM image of the β", and elemental distribution map of (b) Al, (c) Mg, (d) Si, (e) Cu, and (f) schematic diagram of the suggested structure. Color codes are as follows: blue = Al, green = Mg, red = Si, yellow = Al and Mg column, dotted circle shows Cu containing site. The scale bar indicates 0.5 nm.