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The morphology and orientation relationship variations of Q′ phase in Al–Mg–Si–Cu alloy

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ABSTRACT

The morphologies and orientation relationships (OR) of the Q′ phase in an over-aged Al−–Mg–Si–Cu alloy were characterized by atomic resolution high-angle annular dark-field scanning transmission electron microscopy. Statistical results revealed that the OR of the rod-like Q′ phase with the Al matrix has a variable angle ranging from ~3.4° to 15.5° between $(1120)_{Q'}$ and $(510)_{\alpha}$, while the lath Q′ phase has a conventional OR with a constant angle of 11°. Such variations likely to be attributable to the ordering of Si-network in the Q′/β″ phase formed in the peak aging condition.

1. Introduction

The Q-phase is a quaternary equilibrium phase that formed during the age hardening treatment in 6xxx series Al–Mg–Si–Cu alloys, 2xxx series Al–Cu–Mg–Si alloys and Al–Si–Mg–Cu casting alloys such as A319 [1]. The Q phase has a lath or rod morphology with their long axes parallel to $\langle 001\rangle_{\alpha}$. The crystal structure of Q phase is generally known to be hexagonal (P6) with lattice parameter $a_Q = 10.39$ Å and $c_Q = 4.02$ Å [2–5]. But the exact stoichiometry composition of Q phase has been found to vary between different studies, such as, $Al_4Cu_2Mg_8Si_7$, $Al_5Cu_2Mg_8Si_6$ and $Al_4Cu_1Mg_5Si_4$ [6]. It is commonly known that the Q phase has a $\{510\}_{\alpha}$ habit plane, and its orientation relationship (OR) with the α-Al matrix is $[0001]_Q$ // $[001]_{\alpha}$ and $(1120)_Q$ $(510)_{\alpha}$ [7,8]. The Q′ phase is a metastable version of Q phase with a similar hexagonal unit cell and composition, which plays an important role in the precipitation hardening of Al–Mg–Si–Cu alloys.

The structure, crystallography and the mechanisms of nucleation and growth of the Q′ phase are remaining the subject of intensive investigation, and a clear understanding of the orientation relationships (OR) of the Q′ phase are essential for controlling and modifying the precipitation strengthening of Al–Mg–Si–Cu alloys. Recent work by M. Fiawoo et al. [9] had revealed multiple ORs between Q phase and the Al matrix, and at least six different ORs were identified. Similar observations were also detected in S phase in the over-aged Al–Cu–Mg alloys, which adopt a continuous or near-continuous range of ORs [10,11]. By far, the underlying mechanism of the variations of ORs in Q (Q′) phase is still unknown. In the present study an atomic-resolution high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) imaging technique is used to examine the variations of ORs and morphologies in Q′ phase, and the forming mechanism of the multiple ORs is discussed.

2. Experimental

An alloy with chemical composition of Al–0.62Mg–1.11Si–0.5Cu–0.15Fe–0.06Mn (wt%)was used for all the experiments. The alloy was solution heat treated (SHT) at 560 °C for 30 min, water quenched and aged at 180 °C for 2 h and 4 days, which corresponds to the peak aging and over-aging stage. STEM samples were prepared by electropolishing using a Tenupol 5 machine (Struers) with 30% nitric acid/70% methanol solution at −30 °C. HAADF-STEM imaging was performed using a spherical aberration probe corrected FEI Titan G2 60-300 TEM with a Schottky field emitter operated at 300 kV. The probe diameter was 0.08 nm and the collection angle of the HAADF detector was in the range of 45–150 mrad. A beam current of 305 μA was measured. Owing to the Q′ phase orientation relations, all STEM images in this work were taken along a $\langle 001\rangle_{\alpha}$ zone axis. To reduce noise, all the HAADF-STEM images were Fourier filtered with an aperture encompassing all the visible spots in the Fourier transform.

3. Results and discussion

The Q′ phase formed in the alloy has a lath- or rod-like morphology with the long axis parallel to the $[001]_{\alpha}$. Fig. 1 shows a HAADF-STEM image ($\langle 001\rangle_{\alpha}$ zone) of cross-section of a typical lath Q′ phase formed during over-aged condition (aging at 180 °C for 4 days). Owing to the

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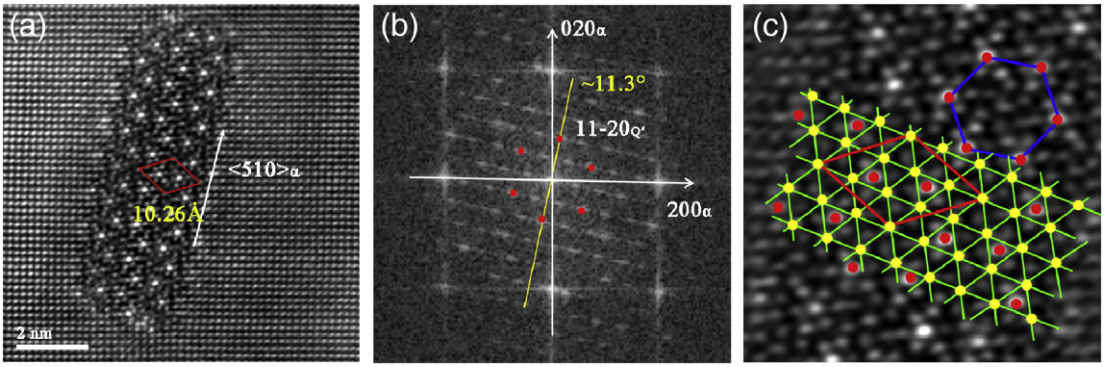

Fig. 1. (a) HAADF-STEM images of cross-sections of lath Q′ phases taken along $[001]_{\alpha}$. (b) the corresponding FFT patterns of (a), (c) the enlarged images of (a). The Cu and Si-rich columns are marked by the red and yellow dots, the Q′ unit cell is indicated by red lines, Cu network by blue lines and Si network by green lines.

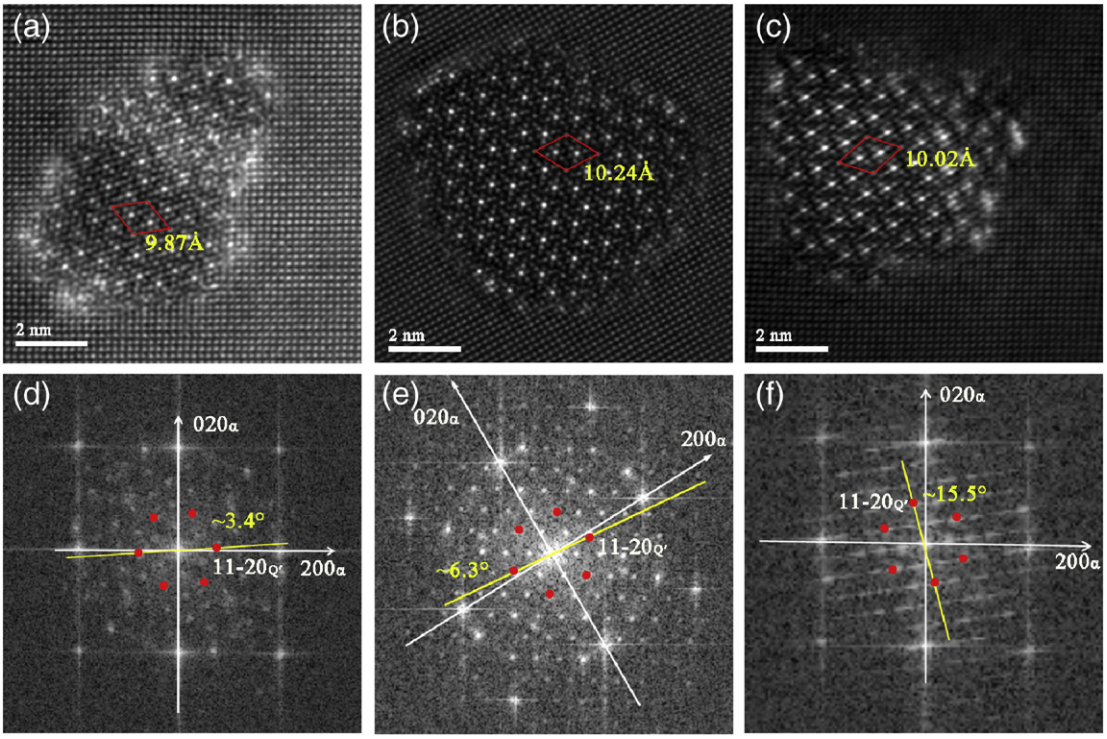

Fig. 2. (a, b, c) HAADF-STEM images of cross-sections of rod Q′ phase; and (d, e, f) corresponding FFT patterns of (a), (b) and (c), respectively, taken along $[001]_{\alpha}$. In (a, b, c) the Q′ unit cell is indicated by red lines.

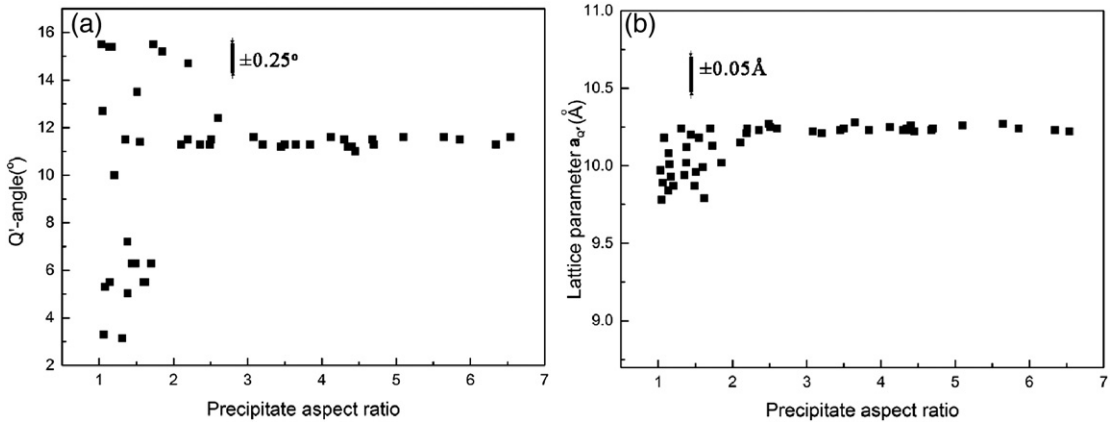

Fig. 3. Statistics of the Q′-angle and the lattice parameter $a_{Q'}$ of different Q′ phase particles plotted as a function of aspect ratio.