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FORMATION OF A MODIFIED β' PHASE IN ALUMINUM ALLOY 6061

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Introduction

Aluminum alloy 6061 belongs to the class of commercial wrought aluminum alloys which has magnesium and silicon as its principal alloying elements. Its nominal composition is 1.0 wt%Mg, 0.6 wt%Si, 0.30 wt%Cu, and 0.20 wt%Cr (1). Alloys with compositions similar to this are reported to exhibit the precipitation behavior of a ternary Al-Mg-Si alloy (2, 3), with a metastable precipitation sequence leading to the equilibrium phase $\beta(Mg_2Si)$. Results by Suzuki, et al. (4), in a study of Al-Mg-Si alloys with small copper additions, indicate that this may not be the case. They claim that, for $0.10 \leq C_{Cu} \leq 0.75$ wt%, an additional intermediate phase (Q') forms, which is based on the quaternary equilibrium phase $Q(Al_5Cu_2Mg_8Si_6)$ (See also (5, 6)). They were unable to determine a crystal structure or any other parameters for this precipitate. Observations made by the present authors during an investigation of the effects of welding on alloy 6061 support an assertion that a precipitate other than those based on $\beta(Mg_2Si)$ forms in this alloy. This paper is a report of those observations and compares the precipitate found in alloy 6061 with those in the Al-Mg-Si ternary and Al-Mg-Si-Cu quaternary systems. To avoid confusion with precipitates in the ternary or quaternary systems, the precipitate of interest in alloy 6061 will be designated B'.

Experimental

It was found that B' could be produced in alloy 6061 in a number of ways. Its initial observation (in this study) came as a result of a two-step aging treatment. This occurred when a specimen of 6061-T6 (aged to a commercial temper) was subjected to 350°C for one minute. Further investigation revealed that B' could be formed during one-step aging treatments (solution + age). It was also found that B' could form in the heat affected zone during welding of alloy 6061. The examples shown in this paper will be from material subjected to a two-step aging treatment (solution@530°C → WQ → 8hr@180°C + 40min@350°C). This produces a well-formed precipitate from which morphology, habit plane, crystal structure, crystal orientation, and composition may be deduced. The study was carried out using a JEOL 120CX electron microscope.

Results and Discussion

The general characteristics of the B' precipitate may be seen in Figures 1 and 2. Figure 1 is a bright field image of alloy 6061 containing this phase. The foil orientation is $[001]_{Al}$. The B' precipitates lie along the <100> directions of the matrix. Two of the variants of B' may be seen easily. They are the long precipitates aligned along the horizontal and vertical drections of the photograph ($[100]_{Al}$ and $[010]_{Al}$, respectively). There appear to be two types of these, "thick" and "thin". The reason for this is the morphology of B'. Examination of the third variant (end-on) reveals that the cross-section of the precipitates is rectangular, meaning that the overall shape of the particle is lath-like. The end-on variant may be seen in Figure 1 and is rather obvious in Figure 2. Figure 2 is a dark field image (B' reflection) from a different area of the foil. In addition to the morphology it may be noted that, while the axial direction of the precipitate is $\langle 100 \rangle_{Al}$, the width and thickness directions of the lath are 10-12° from the cube directions of the matrix. This corresponds to a habit plane close to, if not exactly, $\{015\}_{Al}$. Each variant possesses four different but equivalent orientations, making a total of twelve orientations for B'. For example, the $[001]_{Al}$ variant (axial direction) may possess lath-like precipitates with any of four habit planes: $(\bar{1}50)_{Al}$, $(150)_{Al}$, $(510)_{Al}$, $(5\bar{1}0)_{Al}$. The end-on precipitates in Figure 2 may be seen to exhibit all four orientations.

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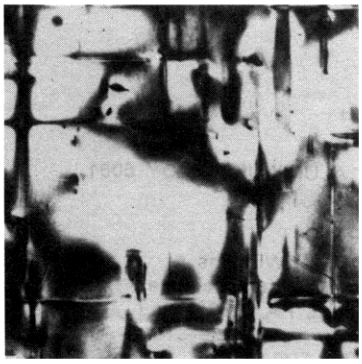

FIG. 1
Bright field image showing B'.
Foil normal near $[001]_{Al}$

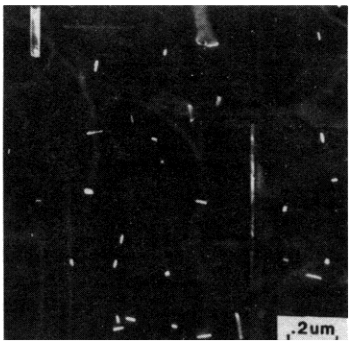

FIG. 2
Dark field image showing B'.

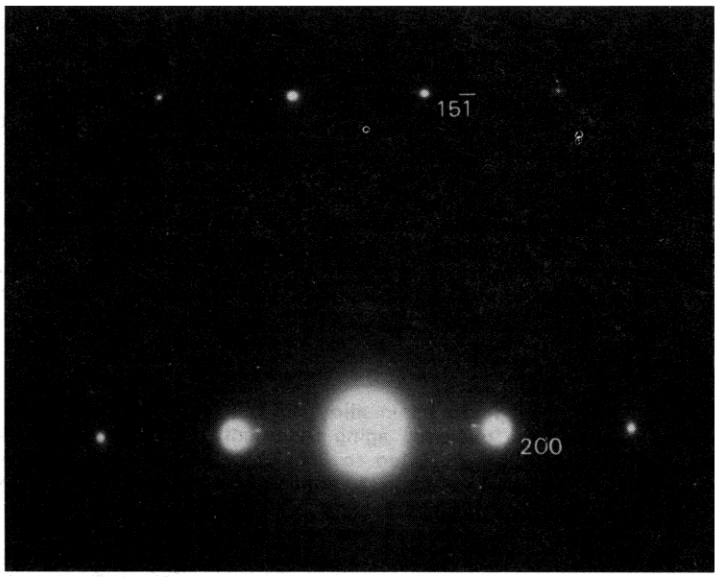

FIG. 3

$[015]_{Al}$ Diffraction Pattern

An analysis of the crystal structure of B' is complicated by the fact that up to twelve orientations may produce diffraction effects. This difficulty may be circumvented to a large degree by considering a diffraction pattern in which some of the reflections from the variants have an obvious orientation with the matrix. The $[015]_{Al}$ diffraction pattern was found to be of this type (Figure 3). The precipitate spots of interest are those lying along the $[05\bar{1}]_{Al}$ direction (vertical) from the $(000)^*$, $(\bar{1}00)^*$, $(\bar{2}00)^*$, $(100)^*$, and $(200)^*$ matrix positions. Only two orientations are represented. There are two types of spots; some are sharp while others are somewhat elongated. These belong to the two orientations of the $[100]_{Al}$ variant with thickness directions of $[015]_{Al}$ and $[05\bar{1}]_{Al}$, respectively. (The sharp spots belong to the laths whose broad face lies in the plane of the foil and the elongated ones to the laths whose broad face lies perpendicular to that. See Reference (7).) Each of these types of spots appears to form a regular array. The intensities of the spots vary, possibly due to structure factor effects. Since the habit plane of B' is $\{015\}_{Al}$, it follows that the crystal structure may be described in terms of an orthogonal lattice with axes parallel to the faces of the precipitate (two axes along $\langle 015\rangle_{Al}$ and one along $\langle 100\rangle_{Al}$). Measurement of the reciprocal lattice distances result in an orthorhombic real space lattice with

parameters of a=9.0A for the thickness direction and b=5.2A in the width direction. The lattice parameter in the axial direction is equal to the lattice parameter of aluminum, 4.05A (= c).

A $[001]_{Al}$ diffraction pattern generated from the above results for B' is shown in Figure 4. Only one orientation is represented, $(001)_{B'} \parallel (001)_{Al}$; $[100]_{B'} \parallel [5\bar{1}0]_{Al}$. This is an end-on precipitate with the thickness direction ($[100]_{B'}$) the same as the spot elongation. Figure 5 is a schematic $[001]_{Al}$ pattern representing only the above orientation. It was drawn from the actual pattern [not shown]. (The $[001]_{Al}$ pattern contains reflections from all twelve B' orientations.) It may be seen that there are extra spots in Figure 5 that are not accounted for in Figure 4. These spots lie at the centers of the rectangular cells formed by the precipitate reflections in the latter. In this light, the crystal sructure of B' may be interpreted in either of two ways: (1) The structure is base-centered orthorhombic (extra occupied site is ½,½,0). In this case the "a" and "b" lattice parameters would be doubled, with a=18.0A, b=10.4A, and c=4.05A. (2) The structure is hexagonal. The diffraction spots also correspond to a hexagonal cell (special case of orthorhombic) with a=10.4A and c=4.05A.

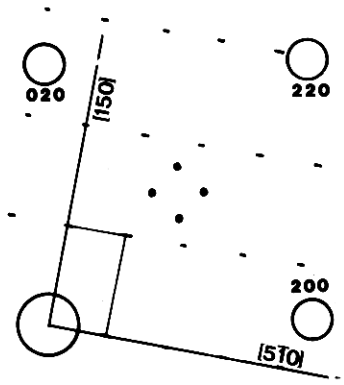

FIG. 4
$[001]_{Al}$ diffraction pattern generated from $[015]_{Al}$ pattern.

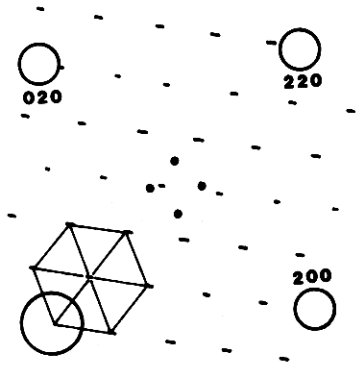

FIG. 5
$[001]_{Al}$ diffraction pattern based on the actual $[001]_{Al}$ pattern.

The misfits between the matrix and precipitate agree well with the observed morphology and orientation. With reference to the orthorhombic lattice of the precipitate, the misfit in the "c" (axial) direction is nearly, if not, zero. The misfit in the "b" (width) direction is less than 1%, while in the "a" (thickness) direction it is approximately -12%. The smallest misfits are along the length and width of the lath, while the largest misfit is through the thickness. The hexagonal lattice parameters of B' (a=10.4A, c=4.05A) are nearly equal to those of the equilibrium quaternary Q phase, $Al_5Cu_2Mg_8Si_6$ (hexagonal, a=10.3A, c=4.05A) (3). (Probably the Q'-Q relationship is similar to that between S' and S in Al-Cu-Mg alloys (8)).

The structure, morphology, and orientation of β' (Al-Mg-Si counterpart to B') has been determined by Jacobs, et al. (9, 10). This phase exists as rods aligned along $\langle 100 \rangle_{Al}$. The structure is hexagonal with a=7.05A and c=4.05A. Each of the three variants has two equivalent but distinct orientations. For the variant $(0001)_{\beta'} \parallel (001)_{Al}$, the two orientations are $[10\bar{1}0]_{\beta'} \parallel [110]_{Al}$ and $[10\bar{1}0]_{\beta'} \parallel [1\bar{1}0]_{Al}$. These are shown in Figure 6a. There are six total orientations of β'. As established above, B' has a total of twelve orientations; four for each of the three variants. For an analagous $(001)_{Al}$ variant, the four possible orientations are: $[10\bar{1}0]_{B'} \parallel [\bar{1}50]_{Al}$, $[10\bar{1}0]_{B'} \parallel [150]_{Al}$, $[10\bar{1}0]_{B'} \parallel [510]_{Al}$, $[10\bar{1}0]_{B'} \parallel [5\bar{1}0]_{Al}$. These are shown in Figure 6b. The hexagonal cell in this figure has its $[10\bar{1}0]$ and $[\bar{1}010]$ directions parallel to $[150]_{Al}$. It might be noticed that two of the other prism directions, $[01\bar{1}0]$ and $[0\bar{1}10]$ (60° and 120° away from $[10\bar{1}0]$, respectively), are nearly parallel to $[\bar{1}10]$ and $[1\bar{1}0]_{Al}$, respectively. The actual difference is about 3½°, meaning that the orientation of B' represents only a slight modification from that of β'.

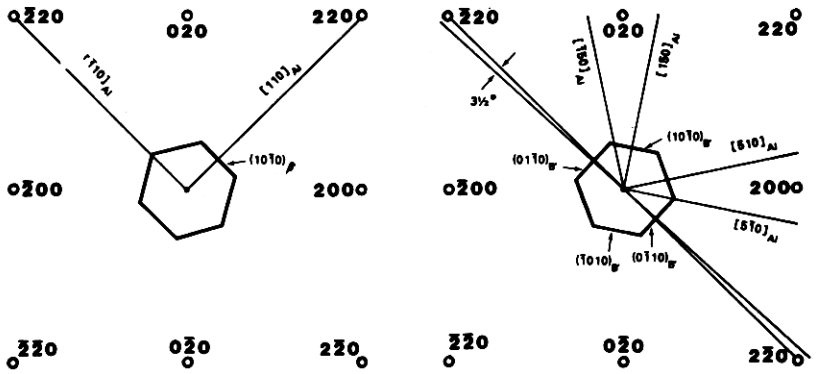

FIG. 6

Orientations of β' and B'.

Conclusions

The B' phase observed in aluminum alloy 6061 differs from the β' phase in ternary Al-Mg-Si alloys. It forms as orthogonal lath-like precipitates with axial directions of $\langle 100 \rangle_{Al}$. The three faces of each lath are mutually perpendicular, with those corresponding to the width and thickness appearing to lie on $\{015\}_{Al}$ planes. The crystal structure may be described in terms of either of two types, orthorhombic or hexagonal. The base-centered orthorhombic lattice may be used to evaluate precipitate-matrix misfit and visualize final morphology. The hexagonal lattice is useful for comparisons with the structures of B' and Q, as well as comparisons between the orientations of B' and β'. The "a" hexagonal parameters of B' and Q are nearly identical, differing significantly from that of β'. In addition, the orientation of B' differs only slightly from that of β'.

Acknowledgements

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