Extra Electron Diffraction Spots Caused by Fine Precipitates Formed at the Early Stage of Aging in Al-Mg-X (X=Si, Ge, Zn)-Cu Alloys

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Age-hardenable Al-Mg-Si, Al-Mg-Ge, and Al-Zn-Mg alloys including Cu were investigated by transmission electron microscopy to understand extra diffraction spots that appear in their selected area electron diffraction patterns. These alloys containing Cu exhibit similar extra diffracted spots to each other with diffracted spots or streaks for Al matrix and major precipitates in each alloy. The extra spots cannot be confirmed in Cu-free alloys. The initial cluster, which is based on the β'' -phase in the Al-Mg-Si alloy, is proposed to be MgSi(/Ge)Mg, CuMgSi(/Ge), AlCuMg, and AlZnMg, while the second clusters, which consist of three initial clusters including anti-phase boundary short-range order, are proposed for Cu-containing alloys. [doi:10.2320/matertrans.L-M2016839]

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1. Introduction

It is well known that age-hardenable Al alloys including Mg and Cu, Si, or Zn form Guinier–Preston (GP) zones and a metastable phase before precipitation of the equilibrium phase. For example, 2xxx Al-Cu-Mg alloys form GP (Guinier–Preston–Bagaryatsky (GPB), GPBII/S'') zones and S'-Al₂(Cu,Mg) phases, 6xxx Al-Mg-Si alloys form a GP zone (cluster) as well as β'' - and β' -Mg₂Si phases, and 7xxx Al-Zn-Mg alloys form GP (GP(I), GP(II)) zones and a η' -MgZn₂ phase^{1–5}. Kovarik *et al.*³ have investigated precipitation in an Al–2.96Mg–0.12Si–0.42Cu–0.007Zn–0.25Mn–0.21Fe–0.002Ti alloy (mass%) aged at 453 K. Different selected area electron diffraction (SAED) patterns produced by GPB zones and the S''-phase were obtained before formation of the S'-phase. They have proposed that GPB II zones exist and that that the S''-phase belongs to the Cmmm space group, is fully coherent with the Al matrix, and has the same orientation relationship as the GPB and S'-phase.

In contrast, A. Charai *et al.*² concluded that the S''-phase of Al-Cu-Mg alloys has a monoclinic lattice system and a different lattice parameter from that of the S'-phase, based on high-resolution transmission electron microscopy (HRTEM) images and their observation of different differential scanning calorimetry (DSC) peaks originating from the GPB zone and the S'-phase. The orthorhombic structure proposed by Wolverton⁶ has been modified by Wang and Starink⁴, who proposed based on a TEM study that the GPB2/S'' is a dis-

crete orthorhombic phase that is coherent with the matrix. The addition of Cu to 6xxx and 7xxx alloys can be modified according to the required mechanical properties, and precipitates containing Cu appear to contribute to their strength, e.g., Q'- or Q-phase precipitates in Al-Mg-Si alloys⁷) and η' -phase precipitates in Al-Zn-Mg alloys^{8,9}).

In this study, age-hardenable Al alloys containing Mg and Cu with added Si, Zn, or Ge were fabricated, and then investigated using TEM in order to understand the extra diffraction spots that appear in their SAED patterns and the common zones/precipitates that have been discovered in them during the early stage of aging.

2. Experimental Procedure

Four age-hardenable alloys, denoted AlCuMg, AlMgZnCu, AlMgSiCu, and AlMgGeCu, were fabricated by casting in air, as shown in Table 1. AlMgZn, AlMgSi, and AlMgGe alloys were also prepared for comparison with the Cu-contain-

Table 1 Chemical compositions of alloys (at.%).

alloys	Mg	Si	Cu	Zn	Ge	Ti	Al
AlCuMg	1.2	-	0.98	-	-	-	bal.
AlZnMgCu	3.20	-	0.20	2.70	-	0.01	bal.
AlZnMg	2.80	-	-	2.60	-	0.01	bal.
AlZnMgCu42	1.80	-	0.24	3.30	-	-	bal.
AlZnMg42	1.90	-	-	3.40	-	-	bal.
AlMgSiCu	1.12	0.37	0.2	-	-	-	bal.
AlMgSi	1.10	0.37	-	-	-	-	bal.
AlMgGeCu	0.44	-	0.18	-	0.19	-	bal.
AlMgGe	0.43	-	-	-	0.22	-	bal.

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ing AlMgZnCu, AlMgSiCu and AlMgGeCu alloys. In addition, AlMgZn42 and AlMgZnCu42 alloys were prepared to compare the difference Zn-to-Mg ratios with AlMgZn and AlMgZnCu alloys. Titanium was included in the AlMgZn and AlMgZnCu alloys for refinement of the solidification structure. The ingots were hot-extruded and cold-rolled into 1-mm-thick sheets. These sheets were solution heat-treated at 848 K for 3.6 ks for the AlMgSi and AlMgSiCu alloys, at 873 K for 3.6 ks for the AlMgGe and AlMgGeCu alloys, at 748 K for 3.6 ks for the AlZnMg and AlZnMgCu alloys, and at 773 K for 3.6 ks for the AlCuMg alloy to obtain single-phase solid solutions. After quenching in 273 K chilled water, the sheets were aged under several different conditions in a silicone oil bath. The micro Vickers hardness was measured using an Akashi MVK-EII hardness tester (load: 0.98 N, holding time: 15 s). The aged sheets were electrolytically polished using a mixture of perchloric acid and ethanol (1:9), or nitric acid and methanol (1:3), to prepare thin samples for TEM observation. Accelerating voltages of 120 kV and 200 kV were used to observe these samples by TEM (TOPCON 002B) and high-angle annular dark-field (HAADF-STEM) imaging (Hitachi HD7200), respectively.

3. Results

Figure 1 shows age-hardening curves for each alloy used in the present study. Each exhibits a peak hardness typical of an age-hardened alloy. The single and double red arrows indicate the aging time of the samples observed by TEM.

Figure 2 shows bright-field TEM images of the AlCuMg, AlMgGeCu, AlMgSiCu, and AlZnMgCu alloys for each aging condition marked by the double arrow heads in Fig. 1. Fine precipitates typical of age-hardened Al alloys can be seen in the images, e.g., the AlZnMgCu alloy contains disc-shaped precipitates¹⁰. The AlCuMg, AlMgSiCu, and AlMgGeCu alloys contain particles and short needles parallel to the $\langle 100 \rangle$ direction of the matrix in their cross-sections^{1-4,11}.

Figures 3(a)–3(c) show SAED patterns obtained for the aged AlMgGeCu, AlMgSiCu, and AlZnMgCu alloys, for which TEM images are shown in Fig. 2(b)–2(d). The diffraction spots and split streaks correspond to zones and metastable

phases in these alloys, e.g., mono-, multi-layer GP zones¹², or fine β'' phase¹³ in Al-Mg-Si or Al-Mg-Ge alloys, and η' and fine η phase in Al-Zn-Mg alloy¹⁰. SAED patterns for Cu-free alloys aged for the same amount of time were also obtained, as shown in Fig. 3(d)–3(f). Comparing Figs. 3(a)–3(c) and Figs. 3(d)–3(f), extra diffracted spots marked by white arrows in the former set can be clearly confirmed. Figure 4 shows SAED patterns obtained for underaged AlCuMg, AlMgSiCu, AlZnMgCu, and AlMgGeCu alloys, for which the aging conditions are indicated by single arrow heads in Fig. 1. The extra spots marked by the white arrows in Figs. 3(a)–3(c) are also confirmed in the SAED patterns, although their intensities are weaker than of those in Fig. 3 due to the short aging time. In particular, these extra spots are in good agreement with the ones presented in Fig. 4(a) for the AlCuMg alloy. This implies that the same precipitates exist in the Cu-containing alloys for those aging conditions.

The extra spots confirmed for the Cu-containing alloys were analyzed in detail. Figure 5(a) shows the same SAED pattern for the AlCuMg alloy as that presented in Fig. 4(a). Figure 5(b) shows an illustration of a SAED pattern reported by Kovarik *et al.*³ They used an Al–2.96%Mg–0.42%Cu–0.12%Si–0.25%Mn–0.21%Fe–0.007%Zn–0.002%Ti alloy (mass%) aged at 453 K for 8 h, obtained TEM images, SAED patterns, and HRTEM images, and proposed a crystal model of GPB-II composed of Cu and Mg atoms, as shown in Fig. 5(c). The crystal model has an orthorhombic C-centered lattice with parameters of $a = 0.404$ nm and $c = 1.212$ nm¹⁴. The unit cell is a one-dimensional superlattice with an incorporated anti-phase boundary (APB) along one lattice direction. Figure 5(d) shows a simulated diffraction pattern generated using the crystal model. The diffraction spots with higher intensity are in good agreement with the coordinates

Fig. 1 Age-hardening curves of each alloy used in the present study.

Fig. 2 Bright field TEM images of each alloy for each aging condition marked by the double arrow heads in Fig. 1. (a) AlCuMg (473 K, 0.24 ks), (b) AlMgGeCu (423 K, 1200 ks), (c) AlMgSiCu (473 K, 6.0 ks) and (d) AlMgZnCu (423 K, 60 ks) alloys.

Fig. 3 SAED patterns obtained for Cu added and Cu free alloys. (a) AlMgGeCu (423 K, 1200 ks), (b) AlMgSiCu (473 K, 6.0 ks), (c) AlMgZnCu (423 K, 60 ks), (d) AlMgGe (423 K, 1200 ks), (e) AlMgSi (473 K, 6.0 ks) and (f) AlMgZn (423 K, 60 ks) alloys.

Fig. 4 SAED patterns obtained for underaged Cu added alloys. (a) AlCuMg (473 K, 0.24 ks), (b) AlMgGeCu (423 K, 3.84 ks), (c) AlMgSiCu (473 K, 0.24 ks) and (d) AlMgZnCu (423 K, 0.96 ks) alloys.

marked by white arrows in Fig. 5(a) and white circles in Fig. 5(b). The diffraction spots illustrated by the white circles in Fig. 5(b) are also completely superimposed on the extra diffraction spots observed for all of the Cu-containing alloys, which are marked by the white arrows in Figs. 3(a)–3(c) and 4. The intended meaning is not clear. Do you mean “This indicates that the Cu-containing alloys are quite similar in structure to the that proposed by Kovarik *et al.* for the GPB-II zone in Al-Cu-Mg alloy.

The SAED patterns of the AlZnMgCu alloy shown in Figs. 3(c) and 4(d) are also similar to the GP(I) zone in the Al-Zn-Mg and Al-Zn-Mg-Cu alloys reported by Berg *et al.*⁵⁾ and Buha *et al.*¹⁵⁾ Berg *et al.* proposed a crystal model for

GP(I) composed of Al, Zn, and Mg atoms, as shown in Fig. 6(e), which is internal order described by four-doubling of an Al cell in one cube direction. Figure 6(d) shows part of a simulated SAED pattern generated using this crystal model. Part of the simulated SAED pattern for GPB-II shown in Fig. 5(d) is also shown in Fig. 6(b). The higher intensity diffracted spots in Fig. 6(d) are similar to the coordinates marked with white circles in the dashed square shown in Fig. 6(c), although the size of the GP(I) unit cell in Al-Zn-Mg alloys proposed by Berg *et al.*⁵⁾ is different from that of the GPB-II unit cell in Al-Cu-Mg alloys proposed by Kovarik *et al.*¹⁴⁾ Since GPB-II is based on three unit cells of the Al lattice, the spacing of the extra diffraction spots is different from that in the models of Kovarik *et al.* and Berg *et al.*, as can be seen in Figs. 6(b) and 6(d), respectively. The ratio of the spacing between the 000 and extra diffraction spots is 0.83 for GPB-II and 0.87 for GP(I), whereas the ratio of the spacing between the 000 and 220 spots is 1.0. The spacing of the practical diffraction spots in Figs. 6(a) and 6(c) is equal, and it has been measured as 0.84, which is nearly equal to the spacing of GPB-II, as can be seen in Fig. 6(b). These results suggest that GPB-II zones in Al-Cu-Mg alloys and GP(I) zones in Al-Zn-Mg alloys are quite similar in structure. The SAED patterns for all of the Mg- and Cu-containing alloys studied in the present work include the same extra spots as those of GP-II proposed by Kovarik *et al.*^{3,14)}

4. Discussion

Figure 7 shows illustrations of previously proposed structures for zones^{4,6,14)} in Al-Cu-Mg alloys. Figure 7(a) shows a model proposed by Wolverton⁶⁾ for GPB zones ($\text{Al}_1\text{Mg}_1\text{Al}_1\text{Cu}_1$) in Al-Cu-Mg alloys based on first-principle calculations. This GPB structure has a low-energy coherent configuration in the Al-Cu-Mg system. Figure 7(b) shows a crystal structure for GPB-II zones in Al-Cu-Mg alloys proposed by Kovarik *et al.*¹⁴⁾, which is based on the AuCuII structure presented in Fig. 5(c). Figure 7(c) shows a model

Fig. 5 (a) SAED pattern of AlCuMg alloy aged at 473 K for 0.24 ks as the same as Fig. 4(a), (b) illustration of a SAED pattern reported by Kovarik *et al.*¹⁴ and (c) its crystal model of GPBII. (d) simulated SAED pattern using Fig. 5(c).

Fig. 6 Comparison between SAED patterns of (a) AlCuMg and (c) AlZnMgCu alloys. Simulated SAED patterns using models proposed (b) by Kovarik *et al.*¹⁴ and (d) by Berg *et al.*⁵. (e) a proposed crystal model of GP(I) in Al-Zn-Mg(-Cu) by Berg *et al.*⁵.

proposed by Wang *et al.*⁴) Since none of the simulated SAED patterns were in agreement with the fast Fourier transform (FFT) and SAED patterns of their results, they considered a new GPB2/S" structure constructed from elements of the Wolverton's structure⁶.

Fig. 7 Proposed crystal models in the (a) GPB by Wolverton⁶, (b) GPBII by L. Kovarik *et al.*¹⁴, and (c) GPB2/S" by Wang *et al.*⁴

The electron diffraction pattern for each crystal model has been calculated along three equivalent $\langle 001 \rangle$ directions in Fig. 8, which shows simulated SAED patterns for the three structures in Fig. 7. Most of the differences for these structures are shown in Figs. 8(i)–8(k) in $[001]_m$. The 510 or 710 spots indicated by the arrows are more clearly visible in Figs. 8(j) and 8(k) than in Fig. 8(i) because of the presence of an APB in the structures of Figs. 7(b) and 7(c), while Fig. 8(i) for Wolverton's model shown in Fig. 7(a) does not exhibit those diffraction spots. In the present study, for each alloy containing Cu, the lattice spacing calculated from the extra spots corresponds to a size of three unit cells of the Al lattice, as shown in Fig. 6. As Fig. 8(j) shows 510 spots corresponding to three unit cells of the Al lattice, this model is in good agreement with SAED patterns measured in this study.

Here, the suitable zone is proposed using the following three assumptions:

1. The zone has 3 unit cells of the Al lattice.
2. The zone includes an APB.
3. The zone includes Mg, Si/Ge or Al, and Cu or Zn.

Initially, a part of the β "-phase in the Al-Mg-Si alloy is used for an element of the cluster. Figure 9(a) shows an illustration of an atomic model of the β "-phase in the Al-Mg-Si alloy, which has a monoclinic lattice. The model contains a sub-cell, the so-called "eye" cluster indicated by a square proposed by Hasting *et al.*¹¹) In addition, Kovarik *et al.* have recently reported a structure similar to the "eye" cluster in Al-Cu-Mg alloys, as observed by in their HAADF-STEM study¹⁶). This indicates that these precipitates are likely similar to each other. The "eye" cluster has also been observed in the Al-Mg-Ge alloy in the present work, as shown in Fig. 10, which is a HAADF-STEM image obtained for the β "-phase in Al-0.4Mg-0.2Ge (at.%) alloy aged at 437 K for 6 ks. Those results also support our three assumption described above. Figure 9(b) is an illustration of the "eye" cluster¹¹), based on the distorted Al matrix, fundamentally consisting of Mg and Si, and has good coherence with the Al matrix. Figure 9(c) is also an illustration of the "eye" cluster, which differs from that in Fig. 9(b) in that the displacement is along the $1/2[010]_{Al}$ direction. It shows the Mg-cargo of an octahe-

Fig. 8 Simulated SAED patterns for 3 structures in Fig. 7. (a), (e) and (i) for GPB by Wolverton⁶⁾, (b), (f) and (j) for GPBII by L. Kovarik *et al.*¹⁴⁾, and (c), (g) and (k) for GPB2/S" by Wang *et al.*⁴⁾

Fig. 9 (a) The crystal model of the β'' -phase in Al-Mg-Si alloy proposed by Hasting *et al.*¹¹⁾ (b) an illustration of the "eye" cluster, and (c) an illustration of the "eye" cluster which has the difference of displacement along to $1/2[001]\text{Al}$. This cluster of (b) or (c) is referred as the initial cluster in the present study.

dron, which has dimensions of 0.351 nm and 0.405 nm. In the present study, the "eye" cluster, which we have referred to as the "initial cluster", is the 4th assumption. The mono-layer GP zones, or "Matsuda-phase", in previous studies are also in

good agreement with a part of this cluster^{13,17)}.

Although SAED patterns have been calculated using the initial clusters of Figs. 9(b) or 9(c), extra spots like those in Figs. 3 and 4 were not observed. This means that this initial cluster includes an APB, as in Fig. 7(b), and also has a size of three Al lattice unit cells. Actually, the SAED patterns containing extra spots were obtained for alloys with Cu. Those extra spots do not appear for the Cu-free alloy. It is assumed that the initial cluster can grow to a size of three Al unit cells with an APB if the initial cluster includes Cu atoms in the alloy. Atomic models containing Cu are proposed in Fig. 11. The initial cluster in Fig. 11(a) is the same as that in Figs. 9(b) and 9(c), and consists of Mg and Si or Ge, and is referred to as the MgSiMg or MgGeMg cluster. When the body-centered Mg in the cluster of Fig. 11(a) is replaced with Cu, it becomes the cluster with Cu shown in Fig. 11(b), which is referred to as a CuSiMg cluster. Figure 11(c) shows a cluster of the AlCuMg alloy. Si and body-centered Mg atoms in the MgSiMg cluster are replaced with Cu and Al atoms. This is referred to as the AlCuMg cluster, which has the same size, but different coordinates than the atomic model reported by Kovarik *et al.*¹⁴⁾ The cluster of the AlZnMg alloy is just the AlCuMg cluster with Cu replaced by Zn. which is referred to as the AlZnMg cluster. The value of the bond overlap (BO) for each initial cluster was also calculated using the DV-Xa method¹⁸⁾ to estimate the strength of covalent bonding for each cluster. In this case, the left-hand side of the initial clusters in Figs. 11(a)–11(d) was used for the calculation. The body-centered Mg atoms in the MgSiMg cluster shown in Fig. 11(a) were replaced with Cu, which becomes the initial CuSiMg cluster shown in Fig. 11(b). The face-centered Cu

473K, 6ks Al-Mg-Ge alloy

Fig. 10 (a) HAADF-STEM image of the β'' -phase in Al-0.4 at.% Mg-0.2 at.% Ge alloy aged at 437 K for 6 ks, and (b) atomic model⁽¹¹⁾ superimposed.

Fig. 11 Atomic models for initial clusters ((a)–(d)) and 2nd clusters ((e)–(h)). (a) and (e) for MgSiMg (or MgGeMg), (b) and (f) for CuSiMg, (c) and (g) for AlCuMg, and (d) and (h) for AlZnMg clusters. Light green, blue, red, orange and purple are Al, Mg, Si (or Ge), Cu and Zn atoms.

shown in Fig. 11(c) was replaced with Zn, which is the initial AlZnMg cluster shown in Fig. 11(d). As those BO values were 2.5 for MgSiMg, 2.7 for CuSiMg, 2.7 for AlCuMg, and 2.8 for AlZnMg clusters, the substitution of body-centered

Mg with Cu, or face-centered Cu with Zn in each cluster does not make a remarkable difference between their orbital overlaps. These initial clusters were used to draw the second clusters including APB and three unit cells, like those shown in

Figs. 11(e)–11(h). Calculated SAED patterns using those models are shown in Fig. 12 for three equivalent $\langle 100 \rangle$ Al directions. The fact that the extra spots in Figs. 3 and 4 clearly appear in Figs. 12(i)–12(l) means that these atomic models mostly correspond to actual clusters.

It notes that Figs. 12(i) and 12(l) show 510 diffraction spots. In Fig. 3, Cu-free AlMgSi and AlZnMg alloys do not exhibit extra spots in their measured SAED patterns. This means that MgSiMg clusters cannot include Cu inside their structures, and probably depends on the chemical compositions of the alloys. In the present study, the Mg:Cu ratio in the AlMgSiCu alloy is 5:1, while in the AlCuMg alloy it is 1:1. When the matrix includes enough Mg and Si with Cu, a CuSiMg cluster can form in the matrix. If there is enough Mg and Cu, and no or low Si content, a AlCuMg cluster forms in the matrix of the AlCuMg alloy. The AlZnMg cluster would be formed the same way as the AlCuMg cluster, which means that Cu replaces Zn. Figure 13 shows SAED patterns for Al-Zn-Mg alloys peak-aged at 423 K for 24 ks including a different Zn/Mg ratio with or without Cu. The SAED pattern shown in Fig. 13(a) obtained for the AlZnMgCu42 alloy exhibits extra spots, like those seen in Figs. 3(c) and 4(d). Figure 13(b) obtained for the AlZnMg42 alloy also exhibits extra spots, although this alloy does not include Cu. The AlZnMgCu42 and AlZnMg42 alloys have Zn/Mg = 2, while AlZnMg and AlZnMgCu alloys have Zn/Mg = 1. This means that the AlZnMg alloy can make a second cluster and/or a AlZnMg cluster can include Cu when the Zn/Mg ratio is high and there is enough Zn content, even if there is no Cu.

We conclude that CuSiMg, AlCu(Zn)Mg, and AlZn(Cu)Mg clusters are essential in those alloys, and form or grow to the second clusters prior to formation of the metastable phase. They then transform to the S', Q' or η' phase. On the other hand, the MgSiMg or MgGeMg initial clusters in the Cu-free AlMgSi or AlMgGe alloys can probably form a stringlet zone parallel to $\langle 100 \rangle$ without growth to the second cluster, and transform to metastable phases by stacking of the initial clus-

ters, similar to LEGO[®] bricks, according to the following rules:

1. Each cluster can stack in the direction perpendicular to the Si(Ge) plane.
2. Each cluster can form an array parallel or not parallel to the $\langle 100 \rangle$ Al direction with a displacement of $1/2 \langle 100 \rangle$ Al.
3. Mg, Si, or Ge atoms cannot form arrays with distances of less than 0.203 nm. In general, the required distance is 0.286 nm for $\langle 110 \rangle$ Al and 0.405 nm for $\langle 100 \rangle$ Al.

In the case of alloys for which Mg/Si(Ge) ≥ 2 , the alloy makes monolayer or multilayer zones^{12,17)} from MgSiMg or MgGeMg initial clusters, which arrays along the $\langle 100 \rangle$ m direction, as shown in Fig. 14. Those initial clusters also stack in the $[001]$ Al direction. Alloys for which Mg/Si(Ge) ≤ 1 can form the β'' -phase¹¹⁾ from MgSiMg or MgGeMg initial clusters, as shown in Fig. 15.

5. Conclusions

The SAED patterns for age-hardenable Al-Mg-Si, Al-Mg-Ge, and Al-Zn-Mg alloys containing Cu were investigated by TEM. The results obtained are as follows:

Fig. 13 SAED patterns obtained for Al-Zn-Mg alloys including higher ratio of Zn/Mg = 2. (a) AlZnMgCu42 and (b) AlZnMg42 alloys peak-aged at 423 K for 24 ks.

Fig. 12 Calculated SAED pattern using atomic models in Fig. 11 for 3 equivalent $\langle 100 \rangle$ Al directions.

- (1) Alloys containing Cu exhibited extra diffraction spots in their SAED patterns for precipitates and the Al matrix, while alloys without Cu did not.

Fig. 14 An illustration of atomic model for formation of zone by 3 initial clusters. Each cluster arrays to parallel to $[010]_{\text{Al}}$ with a displacement of $1/2[001]_{\text{Al}}$, and stack to the same $[001]_{\text{Al}}$ perpendicular to the Si-plane.

- (2) The coordinates of the extra spots for all alloys were in good agreement with each other.
- (3) The initial cluster, which is based on the β'' -phase in Al-Mg-Si alloys, has been proposed as $\text{MgSi}(/ \text{Ge})\text{Mg}$, $\text{CuMgSi}(/ \text{Ge})$, AlCuMg , and AlZnMg .
- (4) Based on simulated diffraction patterns, it has been suggested that second clusters, which consist of three initial clusters including short-range order with an APB, exist in the Cu-containing alloys. The initial $\text{MgSi}(/ \text{Ge})\text{Mg}$ cluster cannot grow into a second cluster, and the AlZnMg cluster can contain Zn or replace it with Cu.

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Fig. 15 An illustration of atomic model for the sequence to form β'' -phase by initial clusters. (a) 1 MgSiMg initial cluster, (b) 2 MgSiMg initial clusters array not parallel to $[010]_{\text{Al}}$ with displacement of $1/2[001]_{\text{Al}}$, (c) 2 sets of Fig. 15(b) consisted of 4 MgSiMg initial clusters. Each set has a displacement of $1/2[001]_{\text{Al}}$. (d) a completed form of the β'' -phase.

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