

Correlation of the Aging Characteristics and Deformation Behavior of A357 Alloy

Hanliang Zhu, Jingjie Guo, and Jun Jia

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The mechanical properties, microstructures, and deformation behavior for a cast Al-7Si-Mg casting alloy A357 under various aging conditions have been investigated in the present paper. It is shown that the combination of strength properties and elongation varies with aging parameters. Aging at 165 °C gives the optimum balance of strength and ductility. Transmission electron microscopy (TEM) observation shows that, in the underaged conditions in which Guinier-Preston (GP) zones are formed, the tensile deformation involves dislocations, which cut through the GP zones. Planar slip bands can be seen in the deformed substructures, and the slip bands coarsen with increasing aging temperature or time. In the overaged conditions in which β phases precipitate, the dislocations bypass precipitates and distribute uniformly, except some dislocation tangles around coarser precipitates. When the interaction mode between dislocations and particles changes from shearing to bypassing, the deformation homogeneity greatly increases for the castings with fine β precipitates, which may explain the significant secondary elongation behavior. Based on these studies, a step overaging treatment has been used to improve the overall tensile properties.

Keywords A357 alloy, aging treatment, deformation behavior, mechanical properties, microstructures

1. Introduction

Cast A357 alloy is an age-hardening aluminum alloy. Its mechanical properties are significantly influenced by the aging parameters such as natural aging, preaging, heating rate to the final aging temperature, and artificial aging conditions.[1] Artificial aging temperature and time are the two major parameters. In most cases, A357 castings are aged between 155 and 175 °C for 4 to 6 h to obtain an acceptable combination of strength properties and elongation. The shorter age cycle provides a shorter production time. However, the strength values obtained in these conditions are always low.[2,3] Artificial aging is usually characterized by the behavior in which strength and hardness increase to a maximum and subsequently decrease in the overaged state. The increase in the strength properties is generally associated with the decrease in elongation.[4–7] However, in the titanium-refined A357 castings, secondary elongation behavior is observed in which, initially, the elongation decreases with aging time, reaches a minimum, and then increases to reach a local maximum after a longer aging time, as has been reported by Misra and Oswalt.[8] Interestingly, the secondary elongation peak also corresponds to the optimum strength properties, and this effect is pronounced at small values of dendrite arm space. Misra and Oswalt found by transmission electron microscopy (TEM) that, at the lowest elongation point, there is an equal distribution of Mg_2Si and $TiAl_3$, while at the peak of secondary elongation, only Mg_2Si precipitates are observed. It appears that $TiAl_3$ precipitate delays the normal precipitate kinetics of Mg_2Si. But what happens to the $TiAl_3$ at the lower aging time and why the castings with coarse cell size do not show any secondary elongation behavior cannot be explained. Shivkumar *et al.*[1] have also reported this phenomenon, but no explanation is given in their paper. Further study is required to understand fully this phenomenon and to utilize it for producing the complex premium quality castings that are required to possess the minimum elongation of ~5% in combination with the highest possible strength properties.

In the present work, the mechanical properties of A357 castings under various aging conditions have been studied. The results have been discussed in terms of microstructures and deformation behavior.

2. Experimental Procedure

The A357 alloy for the present investigation was prepared by melting high-purity Al, Mg, and Si and commercial Al-3.37Be, Al-5Ti-0.2B (all in wt.%) master alloy. Melting was carried out in an electric resistance furnace. The melt was degassed and modified by adding 0.6% C_2Cl_6 and 0.5% sodium salt, respectively. The pouring temperature was maintained at 740 ± 10 °C. The metal was filtered with ceramic foam filters before it was introduced into the sand mold *via* a horizontal runner and gating system. The standard samples were cast in the sand molds. All the castings were radiographed, and the samples containing visible defects were rejected. The as-cast test bars were examined carefully by optical microscopy and scanning electron microscopy to determine the quality of the castings. Typical chemical compositions of test bars are shown in Table 1.

All the samples were solution heat treated at 545 ± 3 °C for 12 h and quenched in water at 80 °C. The quench interval was less then 8 s. The samples were naturally aged at room temperature for 24 h. In single-stage aging conditions, samples

Hanliang Zhu, Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, People's Republic of China; and **Jingjie Guo** and **Jun Jia,** School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, People's Republic of China. Contact e-mail: hanliang@public.fhnet.cn.net.

Table 1 Chemical composition of A357 alloy

Element	Si	Mg	Ti	Be	Fe	Al
Wt.%	6.8	0.54	0.18	0.04	0.14	Bal

were aged at temperatures ranging from 155 ± 3 °C to 175 ± 3 °C for times between 4 to 16 h. In step-aging conditions, the samples were preaged at 155 °C for 4 h and finally aged at 175 °C for times between 3 to 18 h. At least five samples were heat treated under identical conditions. The heat treatment process was monitored carefully by positioning several thermocouples in the heat treatment oven.

The samples were subjected to tensile tests in an Instron material testing machine. An extension rate of 2 mm/min was used in all tests. The microstructures were examined in a transmission electron microscope. The foils were cut about 1 mm from tensile fractures.

3. Results

3.1 Mechanical Properties

The mechanical properties of the samples subjected to single-stage and two-stage aging treatments are shown in Fig. 1 and Fig. 2, respectively. It can be seen from Fig. 1 that, at three different aging temperatures, strength properties initially increase with aging time, reach a local maximum, and decrease after a longer aging time (up to 16 h). In the elongation versus aging time curves, a small increase in elongation has been observed at aging times of about 9 to 12 h, and this increase is not accompanied by a reduction in tensile strength.

It can also be seen from Fig. 1 that the samples aged at 155 °C possess higher elongation and slightly lower strength properties. By comparison, when the aging temperature is increased to 175 °C, strength properties are greatly enhanced, while there is a sharp decrease in elongation. The tensile properties of samples aged at 165 °C are between the two values above.

The overall change of mechanical properties of samples subjected to two-stage aging treatments is similar to that of samples subjected to single-stage aging treatments. The samples possess higher elongation than that of those only aged at the temperature of 175 °C for the same time. Ultimate tensile strength of 330 to 340 MPa and elongation of 5 to 6% have been observed in samples aged at 175 °C for 10 to 12 h after preaging. Such a combination of strength and elongation is extremely desirable in complex, premium quality sand castings.

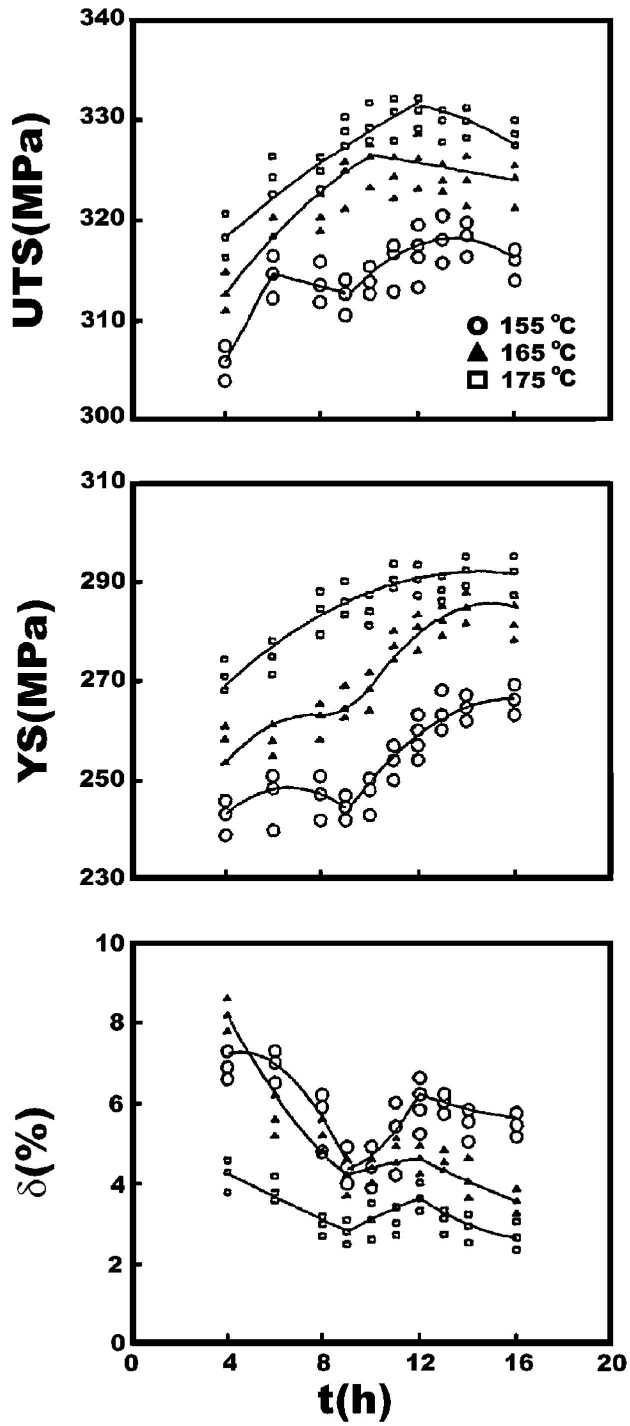

Fig. 1 Mechanical properties of A357 alloy subjected to single-stage aging treatments

3.2 Microstructure

The microstructures of the alloy under different conditions have been examined using TEM. It is difficult to observe Guinier-Preston (GP) zones in Fig. 3. A high density of fine spherical GP zones can be seen at high magnification in the alloy aged at 155 °C for 6 h. Increasing aging time to 8 h leads to GP zones growing and a decrease in density. The GP zones are still spherical and the density is slightly low in the alloy aged at 165 °C for 6 h. The TEM of the alloy aged at 175 °C for 4 h shows that coarser needle-shaped GP zones with lower density are formed.

With prolonged aging, equilibrium Mg_2Si phases (β) form as incoherent platelets and sphere in single-stage and two-stage aging treatments, respectively (Fig. 4 and 5 with A and B indicating precipitate and dislocation, respectively). It can be seen that the platelets formed at 155 °C are thinner and shorter

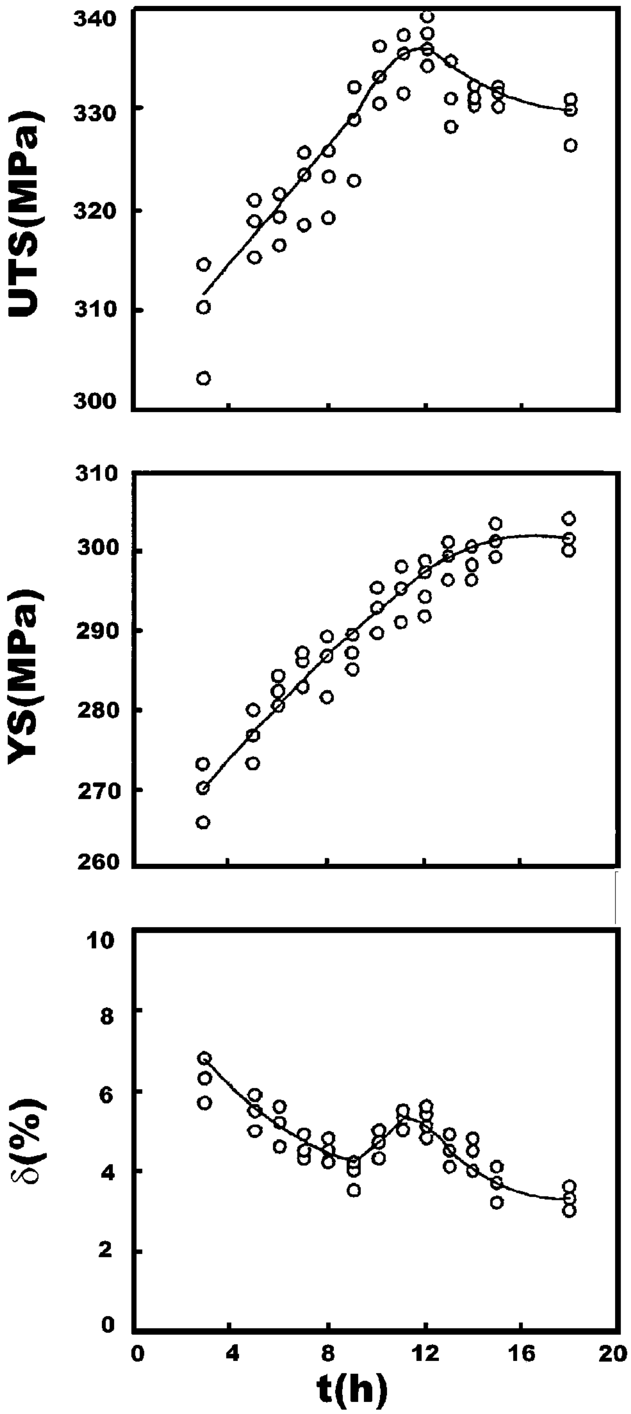

Fig. 2 Mechanical properties of A357 alloy subjected to two-stage aging treatments

than those formed at 175 °C. However, the number of β precipitates at 155 °C is larger. It can also be found from Fig. 4 that the size and number of phases formed at 165 °C are between the two above. In two-stage overaging treatment, the morphology of β precipitates changes from platelets to sphere (Fig. 5) and there is a large number of spherical β phases. The size of β phases also increases with aging time.

3.3 Deformation Behavior

The alloy after a shorter aging treatment exhibits planar slip bands formed mainly by the activation of the slip system (Fig. 3). Slip bands can be distinguished, although they are finer and more closely spaced in the alloy aged at 155 and 165 °C for 6 h (Fig. 3a and c). When aging temperature or time is increased, slip bands become broad and widely spaced (Fig. 3b). When the aging temperature is increased above 175 °C, clear parallel slip bands are formed for 4 h and the dislocation is concentrated on the bands (Fig. 3d). Two slip systems are activated in the casting aged at 175 °C for 8 h, and planar slip bands with two directions can be seen (Fig. 3e).

No slip bands can be seen in the alloy after a longer aging treatment (Fig. 4). Dislocations are bowed out around β precipitates and distribute uniformly in the castings aged at 155 to 165 °C or given two-stage aging treatment at 175 °C for 8 or 12 h (Fig. 4a and b and 5a and b). But there are dislocation tangles and there is a concentration of dislocations in front of the coarser β precipitates in the castings aged at 175 °C for 12 h (Fig. 4c) and the castings finally aged at 175 °C for 18 h after preaging (Fig. 5c). In the present experiment, the amount of variation of $TiAl_3$ has not been observed when aging temperature or time is increased.

4. Discussion

The enhancement of strength properties obtained during the aging treatment is primarily due to the precipitation of metastable phases from the supersaturated solution. The precipitation sequence in Al-Si-Mg alloys is as follows:

$$\text{GP zones} \rightarrow \text{intermediate precipitate } \beta' \rightarrow \text{equilibrium phase } Mg_2Si$$

The decomposition of the supersaturated solution begins with the clustering of silicon atoms.[9] This clustering leads to the formation of coherent spherical GP zones that elongate along the cube matrix direction to assume a needle shape. The GP zones are relatively stable and may exist up to temperatures of about 260 °C.[10] With prolonged aging, GP zones grow to form rods like β' precipitates. The β' phases are semicoherent with the matrix.[11] The final equilibrium phase forms as incoherent platelets on the aluminum matrix. Although the precipitation sequence has been fully understood, there are few papers about the relation between the morphology distribution of particle and aging parameter.

The deformation structures vary with aging conditions too.[12] The distribution of slip dislocations affects tensile properties of alloys. The deformed substructures show the interaction mode between dislocations and particles. After a shorter aging treatment, long and straight dislocation lines and planar slip bands indicate that the dislocations shear GP zones (Fig. 3). After a longer aging treatment, the dislocations are bowed out around the precipitates and no slip bands are formed, indicating that the dislocations bypass the precipitates (Fig. 4).

The castings aged for a short time between 155 and 175 °C contain GP zones. According to the model proposed by Gerold

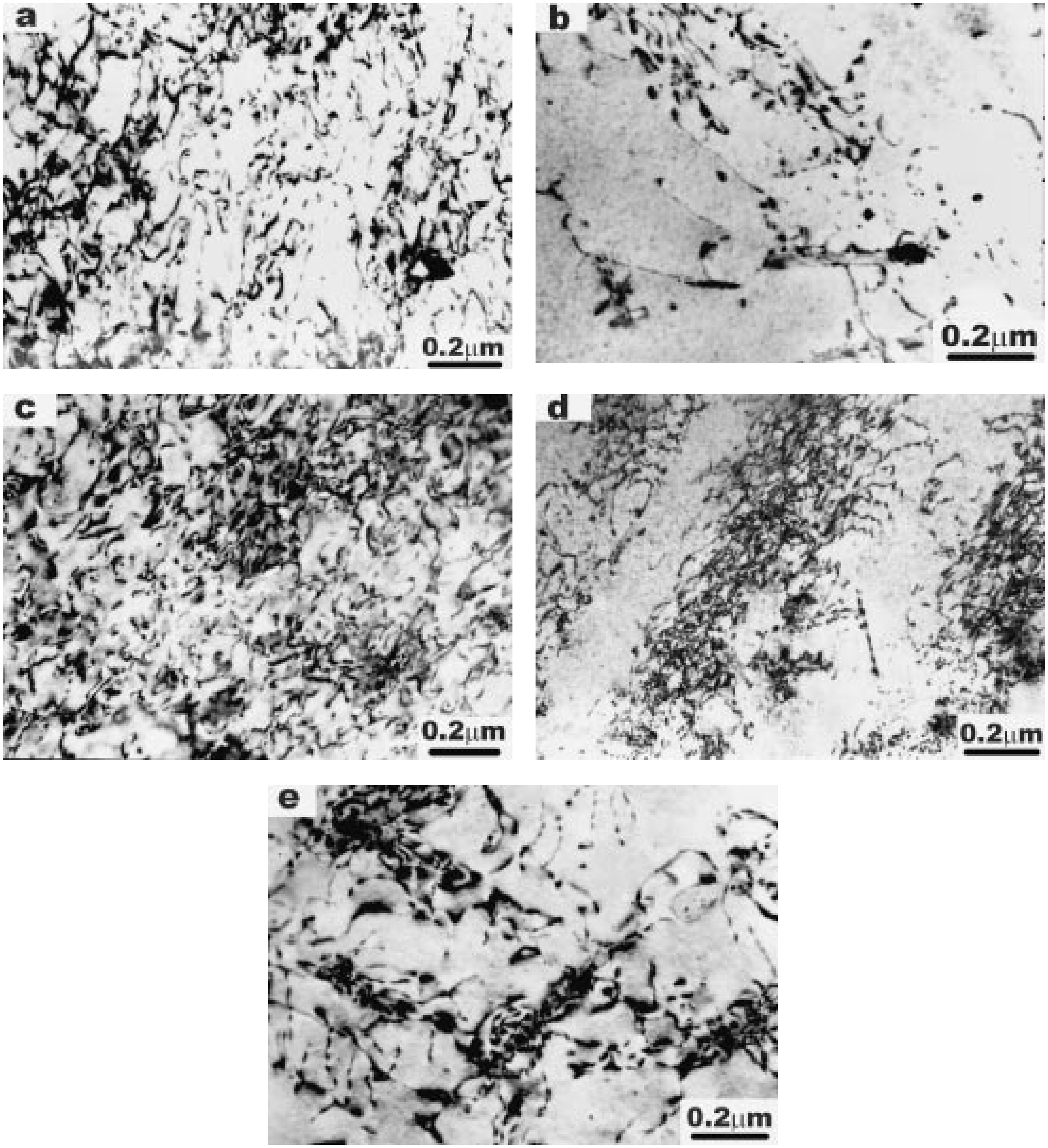

Fig. 3 TEM micrographs of alloy under a shorter aging treatment: (**a**) 155 °C, 6 h; (**b**) 155 °C, 8 h; (**c**) 165 °C, 6 h; (**d**) 175 °C, 4 h; and (**e**) 175 °C, 8 h

and Haberkorn,[13] the stress increases with the size, volume fraction, and strain field of particles. Comparing the samples aged at 175 °C for 4 h to those aged at 155 °C for 6 h, the volume fraction radius and the strain field of the GP zones increase greatly; consequently, the strength is enhanced. However, the deformation is by planar slip and the coarser slip bands indicate that the deformation heterogeneity increases greatly, so the elongation is sharply decreased.

With prolonged aging, the final equilibrium Mg_2Si is formed. According to the model proposed by Orowan,[14] The stress required to force a dislocation between the particles increases with an increase of particle size and a decrease of interparticle

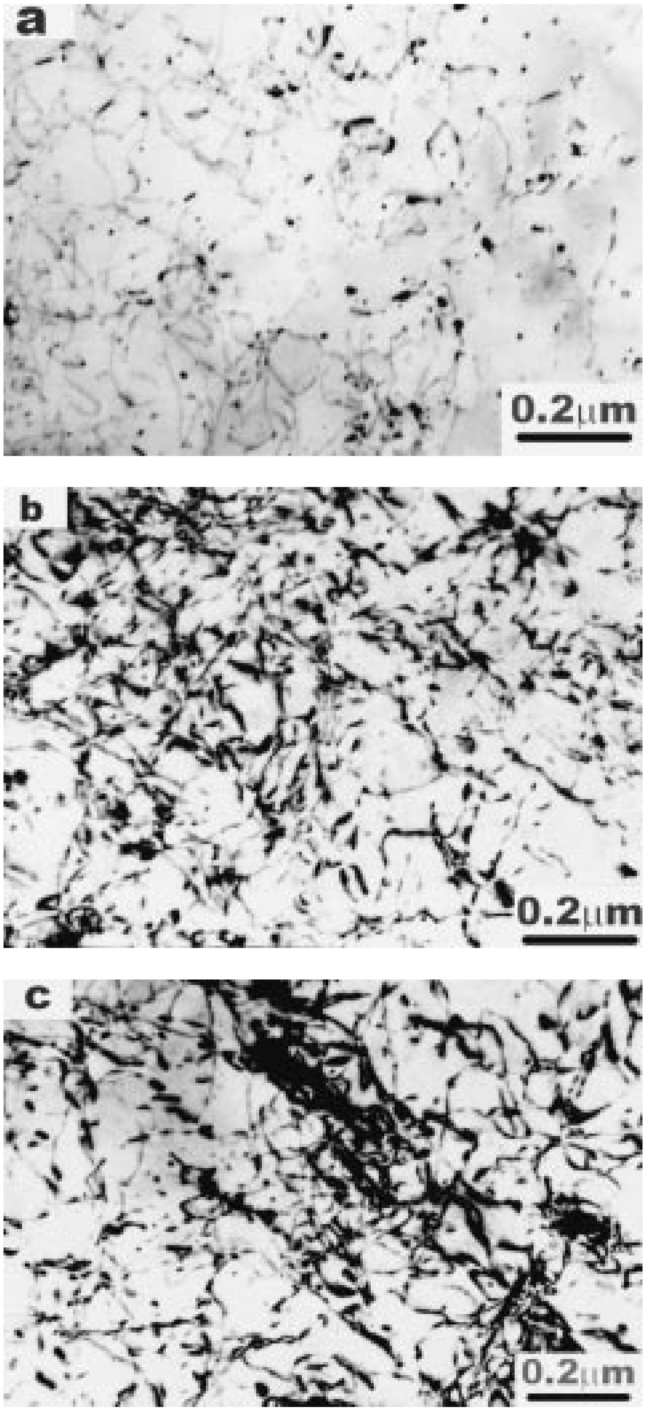

Fig. 4 TEM micrographs of alloy under a longer aging treatment: (**a**) 155 °C, 12 h; (**b**) 165 °C, 12 h; and (**c**) 175 °C, 12 h

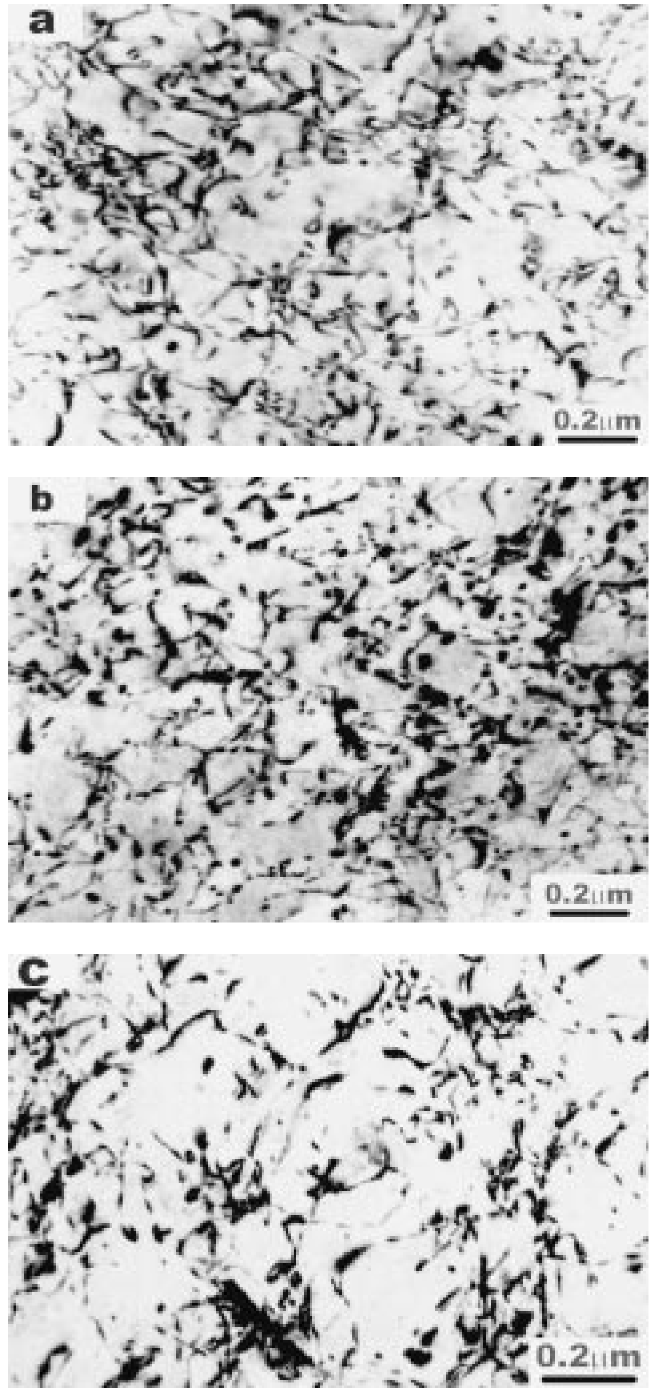

Fig. 5 TEM micrographs of alloy under two-stage aging treatment: (**a**) 155 °C, 4 h + 175 °C, 8 h; (**b**) 155 °C, 4 h + 175 °C, 12 h; and (**c**) 155 °C, 4 h + 175 °C, 16 h

spacing. Comparing the castings aged at 175 °C for 12 h to those aged at 155 °C for the same time, precipitates are of large size with longer spacing. The precipitate size gives more contribution to the strength than the spacing does, so the strength is higher. However, there are more dislocation tangles and concentration in front of coarser β precipitates. Therefore, the castings aged at 175 °C obtain lower elongation than those aged at 155 °C.

After tensile testing, high density GP zones and fine planar slip bands are observed in the castings aged at 155 °C. With increasing aging time, the slip bands become coarser and the deformation heterogeneity increases. Consequently, the elongation decreases with aging time. When GP zones grow to form β precipitates, the interaction mode between dislocations and particles changes from shearing to bypassing. The dislocations distribute more uniformly after tensile tests, and the deformation homogeneity increases. However, β precipitates are coarser in the alloy with large cell size than those with fine cell size, and there are more dislocation tangles and concentration. Therefore, the elongation can continue to decrease and the castings with large cell size can not show any secondary elongation behavior (as shown in Ref 8). However, A357 castings with fine cell size have fine β precipitates. The elongation is greatly enhanced and the significant secondary elongation behavior is observed (Fig. 1 and 2). Continued aging produces a further growth in particle size, and both strength and elongation decrease.

In step overaging conditions, high-density GP zones are formed after preaging. They are relatively stable[10] and grow to spherical β precipitates after final aging at 175 °C for 12 h. Compared to the single-stage aging at 175 °C, β precipitates are of equivalent size and a smaller particle spacing; the strengthening effects increase. At the same time, there are few dislocation tangles, little concentration in the deformed substructures, and uniform distribution of dislocations, so the castings obtain an optimum combination of strength and elongation.

5. Conclusions

- The mechanical properties vary with aging conditions. The castings aged at 165 °C can obtain optimum combinations of strength and elongation. The step overaging treatment can improve the overall tensile properties.
- After a shorter aging treatment between the temperatures of 155 and 175 °C, coherent GP zones are formed and produce local strain. After a longer aging treatment, β precipitates form as incoherent platelets and cause Orowan strengthening.
- In the underaging conditions, dislocations shear GP zones and form planar slip bands after tensile tests. The slip bands become broad and widely spaced with increasing aging temperature or time. In the overaging conditions, dislocations bypass the β precipitate and distribute uniformly, except some tangles around coarser precipitates.
- When the interaction mode between dislocations and particles changes from shearing to bypassing, the deformation homogeneity increases and the castings obtain a significant secondary elongation peak in the elongation versus aging time curves.
- Compared to the single-stage aging at 175 °C, step overaging treatment can improve the overall tensile properties, because precipitates are of equivalent size and shorter particle spacing and the morphology changes from platelets to sphere.

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