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TEM study on microstructures and properties of 7050 aluminum alloy during thermal exposure

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Abstract: The microstructures of 7050 aluminum alloy under different thermal exposure conditions were investigated by means of transmission electron microscopy (TEM), high resolution electron microscopy (HREM) and tensile test. Guinier preston (GP) zone and η' phase are the main precipitates in original 7050 alloy. The orientation relationship between η' and matrix is $[0001]_{\eta'}//[1\bar{1}1]_{\mathrm{Al}}$ and $(10\bar{1}0)_{\eta'}//(110)_{\mathrm{Al}}$. When the alloy is exposed at different temperatures for 500 h, with the thermal exposure temperature increasing, it can be seen under TEM that the precipitates become larger and the width of precipitate free zones (PFZ) becomes larger. The higher temperature the alloy is exposed at, the more the strength is reduced. Both GP zones and η' precipitates getting coarser and the PFZ getting wider should be responsible for the strength decline and elongation rise of 7050 alloy during thermal exposure.

Key words: 7050 aluminum alloy; thermal exposure; microstructure

1 Introduction

The 7050 material is widely used in aviation industry due to its high strength, stress-corrosion-cracking resistance and toughness. It is a high copper and zinc content aluminum alloy designed to be a successor to 7075 aluminum. A key difference between 7050 and 7075 is the addition of zirconium instead of chromium as a recrystallization inhibitor. Furthermore, the high toughness of 7050 alloy can also be achieved by the removal of insoluble phase particles containing the Fe and Si impurities[1−4].

With the development of the aviation industry, it is required that the aviation material should have high temperature oxidation resistance. Therefore, it is necessary to study the effect of thermal exposure on the microstructure and properties of Al alloy. WANG[5] found when 7075-T7351 alloys were thermally exposed at higher temperatures, the growth of precipitates in the grains made the mechanical properties of alloys worse. Some researchers[6] thought that 2D70 alloy could be used at 150 ℃, even below 175 ℃, and there was no obvious change in the microstructures and properties of the alloy, but the alloy displayed the intergranular fracture at high temperature. After studying the effect on the mechanical properties of B/Al composite material, other researchers[7] regarded that the properties of the material were reduced by 20%−30% when being thermally exposed at 300 ℃ for 50−100 h, while the properties began to drop dramatically if the material was thermally exposed at 500 ℃ for a short time. However, so far, little study on the microstructures and properties of 7050 aluminum alloy during thermal exposure has been reported.

The purpose of this work is to supply theoretical and experimental references to safety application of 7050 aluminum alloy by investigating the microstructure and properties of the alloy during thermal exposure.

2 Experimental

The material used in the present work was 7050 alloy, supplied as a plate of 30 mm in thickness. The nominal compositions of the alloy are given in Table 1. The T7651 heat treatment involved solution treatment at 470 ℃ for 50 min and 485 ℃ for 1.5 h, then water quenching to room temperature was performed,

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immediately followed by a 1%−3% stretch and a two stage aging treatment of 6 h at 120 ℃ and 18 h at 165 ℃. Subsequently, all these plates were thermally exposed at 100 ℃, 125 ℃ and 150 ℃ for 500 h.

Table 1 Chemical compositions of alloys (mass fraction,%)

Zn	Mg	Cu	Mn	Cr	Zr	Ti	Fe	Si	Al
6.24	2.26	2.32	0.10	0.01	0.1	0.13	0.07	0.15	Bal.

Tensile tests of specimens, taken along longitudinal direction after thermal exposure, were performed at room temperature. Three discs for TEM observation were punched out directly from samples which were ground down to 0.5 mm in thickness after thermal exposure. These discs were mechanically thinned down to about 150 μm then electropolished using a double jet with a 30% nitric acid solution in methanol at −20 ℃ and 15 V. TEM examinations were performed using a FEI Tecnai G^2 20 operating at 200 kV.

3 Results

3.1 Microstructure of 7050-T7651 alloy

Fig.1(a) shows the original microstructural feature of 7050-T7651 alloy before thermal exposure. It can be seen from Fig.1(a) that some small particles of about 5−10 nm in size are uniformly distributed in the matrix on ⟨011⟩ BF images. These small particles are GP zones, which are formed by homogeneous nucleation in the highly supersaturated solid solution. Their structure consists of several Zn-rich layers on {111} planes. The diffraction pattern in Fig.1(b) confirms such structure by showing streaks running through each spot along ⟨111⟩ direction which is perpendicular to the thin dimension of the GP zones.

Besides GP zones, some plate-like precipitates which are called as η' phases can also be found in Fig.1(a). Fig.2(a) shows a high resolution electron micrograph image of η' phase. The spacing between $(10\bar{1}0)$ planes is 0.43 nm. Fig.2(b) shows the diffraction pattern of strong spots from Al matrix and weak spots from η' phase. Indexing of the weak diffraction pattern confirms that the structure of the η' phase is from the model by PARK and ARDELL[8]. The η' phase has a hexagonal structure with a=0.496 nm, c=1.403 nm and has the orientation relationship as $[\bar{4}8\bar{4}3]_{\eta'}//[001]_{Al}$ and $(10\bar{1}0)_{\eta'}//(110)_{Al}$. It can be confirmed that such orientation is equivalent to $[0001]_{\eta'}//[1\bar{1}1]_{Al}$ and $(10\bar{1}0)_{\eta'}//(110)_{Al}$ as indicated in a superimposed stereogram in Fig.2(c).

From diffraction pattern in Fig.2(b), it can be seen that $(10\bar{1}0)_{\eta'}$ is nearly parallel to $\{220\}_{Al}$ plane. Therefore, η' phase is semi-coherent with matrix lattice.

3.2 Effect of thermal exposure temperature on mechanical properties of 7050-T7651 alloy

The effect of thermal exposure temperature on mechanical properties of 7050 alloy can be seen in Fig.3. Results show that when thermal exposure time is 500 h, with the thermal exposure temperature increasing, the yielding strength and tensile strength of the material decline. The yielding strength and tensile strength are only 329 MPa and 420 MPa, respectively, after the thermal exposure temperature rises to 150 ℃. As for the elongation, it seems little difference between 100 ℃ and 125 ℃, but jumps sharply during thermal exposure at 150 ℃.

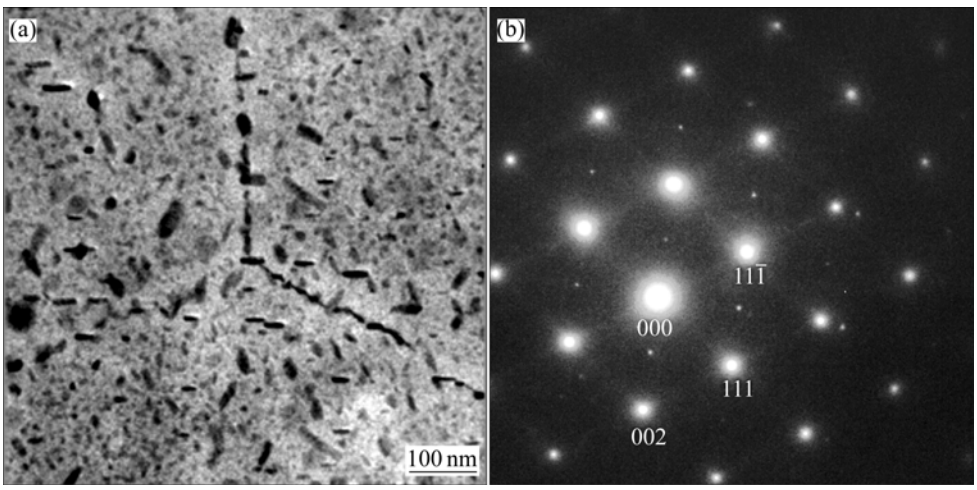

Fig.1 BF image of original microstructure of 7050-T7651 alloy before thermal exposure (a) and its corresponding selected area diffraction pattern along ⟨011⟩ zone axis (b)

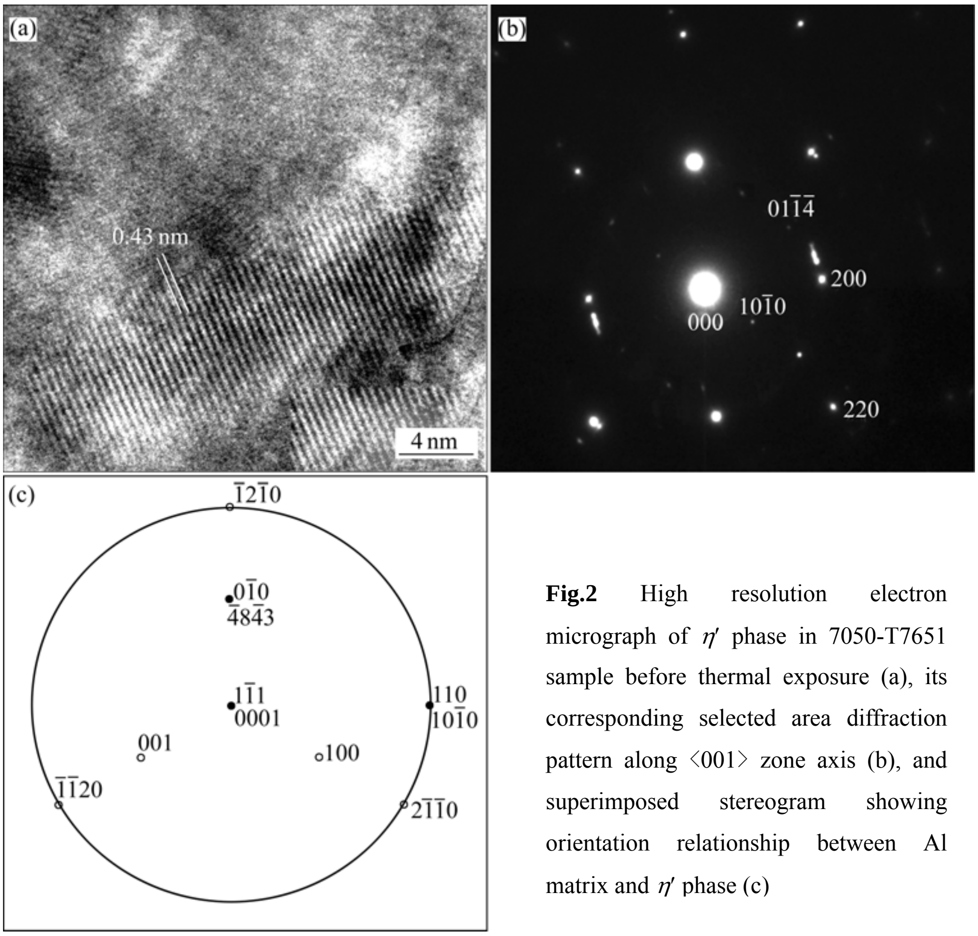

Fig.2 High resolution electron micrograph of η' phase in 7050-T7651 sample before thermal exposure (a), its corresponding selected area diffraction pattern along ⟨001⟩ zone axis (b), and superimposed stereogram showing orientation relationship between Al matrix and η' phase (c)

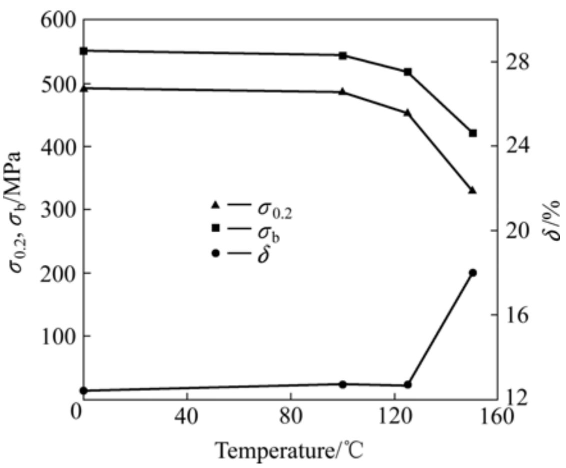

Fig.3 Effect of thermal exposure temperature on mechanical properties of 7050-T7651

3.3 Effect of thermal exposure temperature on microstructure of 7050-T7651 alloy

Figs.4(a)−(d) show TEM images of 7050-T7651 aluminum alloy under different thermal exposure conditions. Compared with the original microstructure of the alloy without thermal exposure (Fig.4(a)), when the alloy is thermally exposed at 100 ℃ for 500 h, precipitates in the grains are still uniformly distributed in the matrix, but the sizes increase obviously. Precipitates on the grain boundaries aggregate and grow up and the lengths of the precipitation phases are measured to be about 60 nm. Furthermore, the widths of precipitate-free-zones (PFZ) near grain boundaries are also increased to approximately 40 nm, as shown in Fig.4(b). Seen from Fig.4(c), when the material is thermally exposed at elevated temperature, 125 ℃ for 500 h, precipitates in the grains and on grain boundaries continue to grow up while the widths of precipitate-free-zones (PFZ) become 60 nm. Finally, when the alloy is under thermal exposure at 150 ℃ for 500 h, precipitates can be obviously found to become larger in size and lower in density. The widths of precipitate-free-zones (PFZ) shown in Fig.4(d) reach about 100 nm.

4 Discussion

The usual precipitation sequence of 7xxx series Al alloys can be summarized as[9]: solid solution → GP zones (GPZs) → metastable η' → stable η ($MgZn_2$). GPZs and η' phase are the main precipitation phases responsible for the high strength of the 7050 aluminum

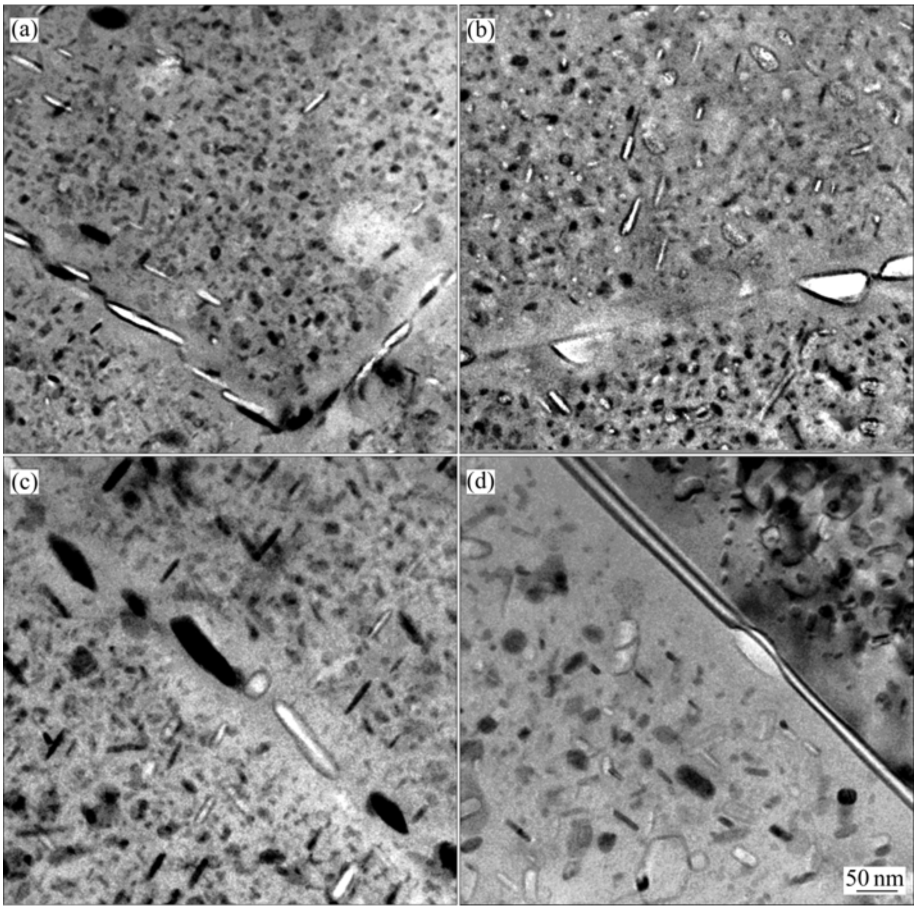

Fig.4 TEM images of 7050-T7651 aluminum alloy under different thermal exposure conditions: (a) No thermal exposure; (b) 100 ℃, 500 h; (c) 125 ℃, 500 h; (d) 150 ℃, 500 h

alloys after T7651 treatment.

During the process of thermal exposure, microstructure and properties of 7050 aluminum alloy are quite different under different thermal exposure conditions. The process of thermal exposure is actually the process of re-ageing. The reaction rate is controlled by the diffusion of the solute atom and vacancy. The temperature is the main influencing factor during this process. The higher the temperature is, the higher the diffusion velocity of the solute atom is and hence the nucleation, growth and coarsening of precipitation phases are accelerated. When 7050-T7651 alloys are thermally exposed at 100 ℃, 125 ℃ and 150 ℃ for 500 h, respectively, with the thermal exposure temperature increasing, precipitates in the grain grow up obviously. It is also found that the density of precipitation phases decreases and the width of precipitation free zone(PFZ) on the grain boundary is broadened(Fig.4).

In this investigation, since the highest thermal exposure temperature is 150 ℃, which is still under the ultimate ageing temperature, the sub-structure strengthening mechanism would not be significantly affected. However, the precipitation hardening may change due to the change of precipitation phases and the features of grain boundaries. Based on the dislocation theory, the contribution of the precipitation phase to the strength of the alloy mainly depends on the interaction of moving dislocation with the precipitates. There are two fundamentally different forms of interaction of dislocations with precipitates: particle bypassing mechanism and particle cutting mechanism. During the process of plastic deformation, when the particle is weak, the dislocation line cuts through such particle; while when the particle size is up to a certain value, bypass of dislocations becomes the dominant mechanism for dislocation motion. The precipitation hardening mechanism depends on the size, the distribution of the particles and the distance between precipitation particles[10]. When precipitation phases take up a certain percentage in the volumetric fraction of the alloy, the smaller the size of the precipitates is and the distance between precipitates is, the better the precipitation hardening in the alloy is. On the contrary, if precipitates aggregate, grow up and coarsen, the density of precipitates decreases, which is bad for alloy strengthening.

In short, after 7050-T7651 alloys are thermally exposed at different temperatures for a long time, precipitates in the alloy grow up and coarsen, which results in reducing the strength of the alloy. Moreover, it is the elevation of the thermal exposure temperature that make the broadening of the precipitate-free-zone (PFZ) near the grain boundary in the alloy more clear. The presence of precipitate-free zone (PFZ) may cause plastic relaxation, which will result in the degradation in strength and elevation in ductility.

5 Conclusions

1) The main precipitates in 7050-T7651 aluminum alloy are GP zones and η' phases. η' phases are identified to be hexagonal with lattice parameters of a=0.496 nm, c=1.403 nm and have orientation relationship with matrix as $[0001]_{\eta'}//[1\bar{1}1]_{\mathrm{Al}}$ and $(10\bar{1}0)_{\eta'}//(110)_{\mathrm{Al}}$. They are semi-coherent with Al matrix.

2) Both GP zones and η' precipitates getting coarser and the PFZ getting wider should be responsible for the strength decline and elongation rise of 7050 alloy during thermal exposure.

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