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Influences of aging temperature and time on microstructure and mechanical properties of 6005A aluminum alloy extrusions

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Abstract: The influences of aging time and aging temperature on the microstructure and mechanical properties were investigated on the 6005A aluminum alloy extrusions. Artificial aging was performed on the alloy extrusions. The aging times were 4, 8 and 12 h, and the aging temperatures were 150, 175 and 200 °C. The results show that the morphologies of the coarse Al(Fe,Cr)Si particles formed in the extrusion process are evolved from granular to rod-like particles with the increase of the aging temperature or the aging time. The volume fraction of the submicron precipitates reaches the maximum value at the aging temperature of 175 °C. AlFeSi particles in size of 1−3 μm are precipitated at the grain boundaries at the aging temperature of 200 °C. The room temperature mechanical properties of the extrusions are more sensitive to the aging temperature than to the aging time. The optimum and stable mechanical properties are achieved when the aging procedure 175 °C, 4−8 h has been performed on the extrusions. The tensile strength and the yield strength in the longitudinal direction of the aged extrusions are more than 300 MPa and 270 MPa, respectively.

Key words: 6005A aluminum alloy; extrusion; aging; Al(Fe,Cr)Si particles; AlFeSi particles; microstructure; mechanical properties

1 Introduction

6005A aluminum alloys are the key materials to the vehicle bodies of high-speed train, metro train and urban light rail due to their excellent extrusion performance, good welding properties, high corrosion resistance and moderate strength [1,2]. It can be manufactured through not only the large extruder to produce complex sectional shapes of large flat hollow profiles with thin wall, but also the extruder to realize the online air cooling or water mist cooling quenching, which makes it become one of the most widely used vehicle body materials [3−5]. However, the quench sensitivity of 6005A aluminum alloys is high, thus aging treatment should be employed after on-line extrusion to achieve stable microstructure and mechanical properties [6−8]. In order to quickly obtain high strength extrusions, the artificial aging process is usually used in industrial production.

Suitable aging process and microstructure are the key factors to the 6005A aluminum alloy extrusions to obtain superior comprehensive mechanical properties. 6005A is a kind of excess Si strengthening Al−Mg−Si series aluminum alloy. As the aluminum alloy of heat treatment strengthening, precipitation strengthening is the main strengthening mechanism of the alloy [9]. The precipitation phases are varied with different aging temperature and time. When the aging temperature is low and the aging time is short, solute atoms gathering zone (GP zone) is not easy to form, leading to low strength after aging (under aging). When the aging temperature is high and the aging time is long, however, the critical nucleus size of the phase precipitated from the supersaturated solid solution can be increased, also resulting in low strength after aging (over aging). The previous studies are mainly focused on the composition optimization, the extrusion process, the quenching sensitivity and the wielding process in 6005A alloys [5,6, 10−14]. Very few research results of the aging process are reported, especially in a short term and single stage aging process, which is beneficial to reducing the production cycle and cost. In order to improve the mechanical properties of extrusions with reduced energy consumption, the short term aging process with a single

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stage can be optimized to achieve the best effect of age hardening in 6005A alloys.

In this work, to determine the optimized aging process of 6005A aluminum alloy extrusions, based on the on-line quenched 6005A extrusion as the research object, the influences of aging temperature and time on the microstructure and mechanical properties were investigated through different short term aging processes with a single stage.

2 Experimental

The 6005A aluminum alloy in the form of extruded profiles with 18 mm thickness was provided by Jilin Midas Aluminum Industries Co. Ltd. The chemical compositions of the experimental alloy compared to the standard 6005A alloy are shown in Table 1. Mg and Si element contents are moderate, and Mg/Si is about 0.79. The extruded profiles were obtained after on-line solid solution and quenching processes. The extrusion coefficient 15−20, the extrusion speed 1.3−1.8 m/min, the solution temperature 520−540 °C and online air cooling quenching were adopted during the processes. The aging treatments were performed at 150, 175 and 200 °C for the times of 4, 8 and 12 h, respectively. The experimental scheme for the aging treatment is shown in Fig. 1. The extrusion profiles were cut along the cross sections for microstructure observation, and along the longitudinal directions for the mechanical properties tests. Tensile specimens in size of *d* 17 mm×220 mm with the gauge section of *d* 12.5 mm×70 mm were prepared by low stress grinding and polishing with 2000 grit emery paper. The microstructure and composition were analyzed by field-emission scanning electron microscopy (FESEM) using a Zeiss SUPRA 55 equipped with an energy dispersive X-ray spectroscopy (EDS) detector.

Table 1 Chemical compositions of experimental alloy compared to standard 6005A alloy (mass fraction)

Element	Composition/%	
	Standard 6005A	Experimental alloy
Si	0.50−0.9	0.70
Fe	0.350	0.13
Cu	0.300	<0.01
Mn	0.500	0.23
Mg	0.40−0.70	0.55
Cr	0.300	0.12
Zn	0.200	<0.01
Ti	0.100	0.042
Al	Bal.	Bal.

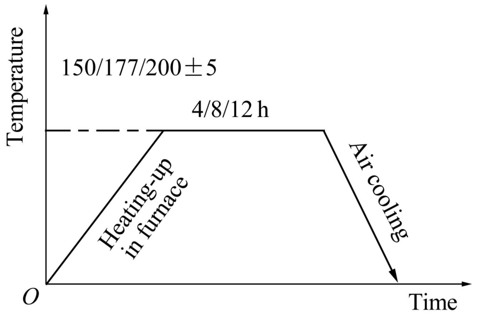

Fig. 1 Experimental scheme for aging treatment

3 Results

Figure 2 shows the low magnitude microstructures in cross section of the 6005A aluminum alloy extrusions after different aging processes. The aged microstructure evolution can be presented from Fig. 2(a) to (i) under conditions of different aging times and temperatures. The coarse particles in white contrast exist after each aging process. The size of the particles is inhomogeneous and a maximum size is about 7 μm. As shown in Fig. 2, with the increase of the aging temperature and time, the grain size does not change obviously, but the size of the coarse particles decreases slightly and the morphology is evolved from granular to rod-like. The composition analysis result shows that, as shown in Table 2, the particles are mainly (Al(Fe,Cr)Si) and a small amount of AlFeSi precipitates.

Table 2 Composition of coarse particles in 6005A aluminum alloy after aging

Element	Mass fraction/%	Mass fraction error/%	Molar fraction/%	Molar fraction error/%
Al	75.46	±0.49	82.53	±0.54
Si	8.51	±0.59	8.94	±0.62
Cr	1.45	±0.23	0.83	±0.13
Fe	14.58	±2.30	7.70	±1.22
Total	100.00		100.00	

Corresponding to Fig. 2, Fig. 3 shows the high magnitude microstructures in cross section of the 6005A aluminum alloy extrusions after different aging processes. As can be seen from Fig. 3, submicron Si-containing precipitates in white contrast exist in the microstructures after different aging processes. The quantity of the precipitates changes obviously with increase of the aging temperature but slightly with increase of the aging time. The mean volume fraction of the submicron Si-containing precipitates increases from 3.9% at aging temperature 150 °C to 6.9% at 175 °C, however, decreases to 3.3% at 200 °C. When the aging temperature is up to 200 °C, some AlFeSi particles in size of about 1−3 μm are precipitated at the grain boundaries.

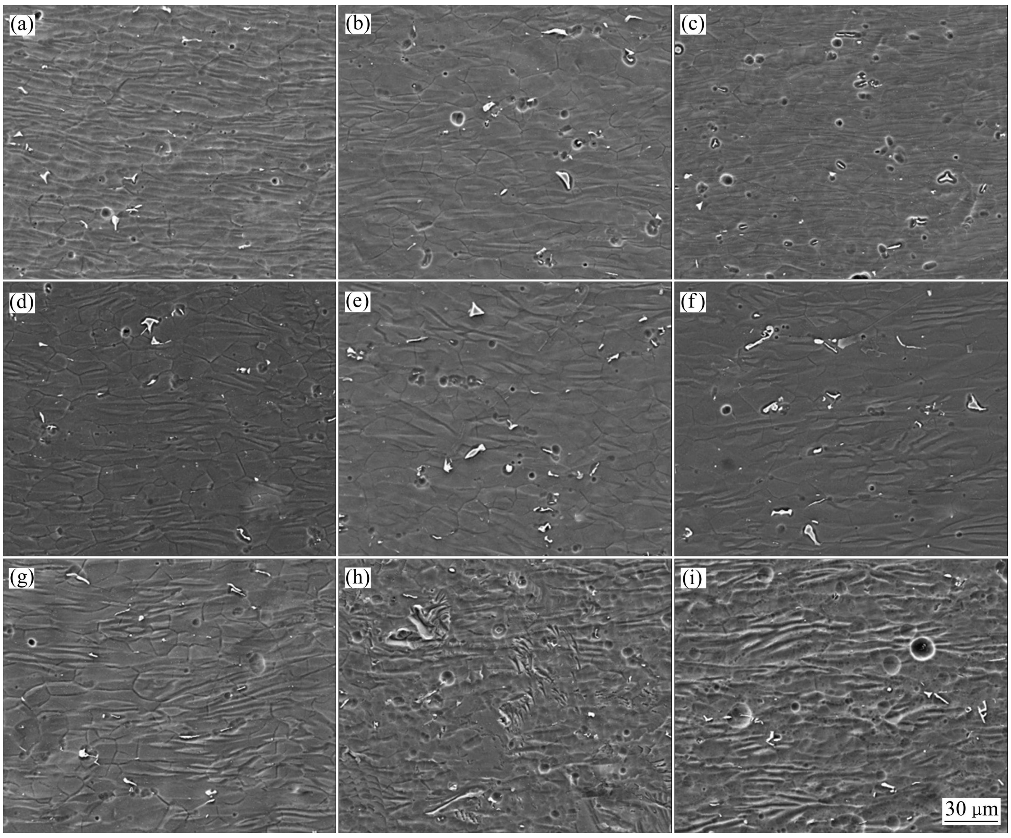

Fig. 2 Microstructures in cross section of 6005A aluminum alloy extrusions after different aging processes: (a) 150 °C, 4 h; (b) 150 °C, 8 h; (c) 150 °C, 12 h; (d) 175 °C, 4 h; (e) 175 °C, 8 h; (f) 175 °C, 12 h; (g) 200 °C, 4 h; (h) 200 °C, 8 h; (i) 200 °C, 12 h

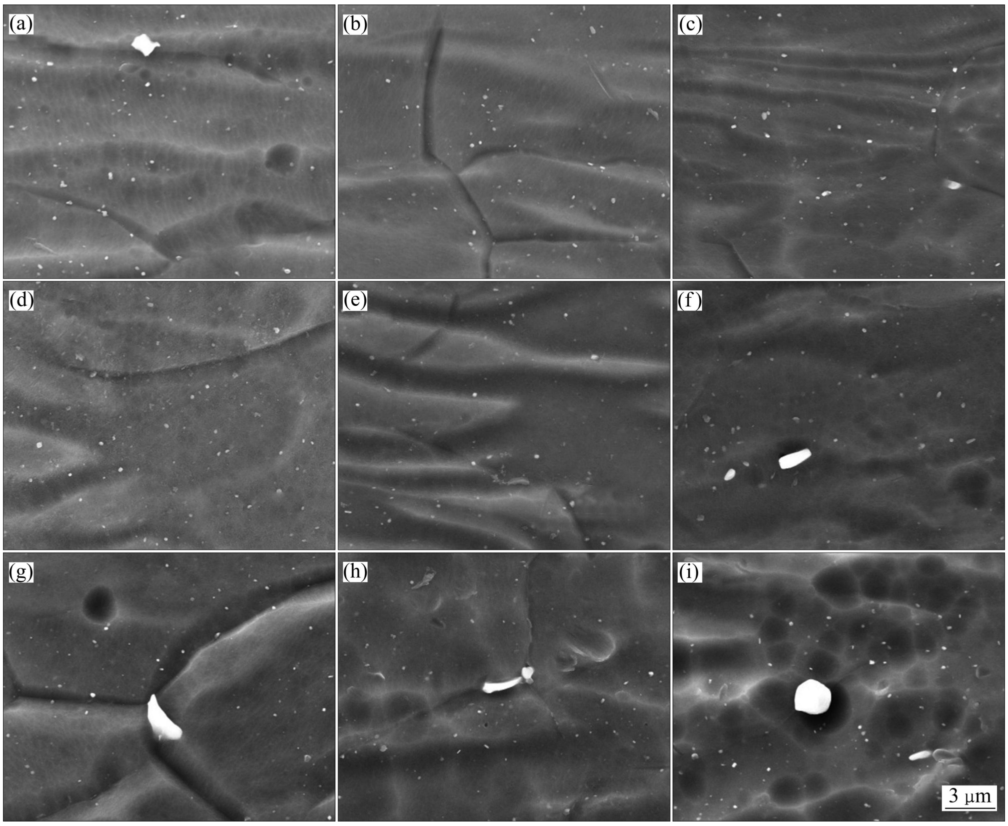

Fig. 3 Microstructures in cross section of 6005A aluminum alloy extrusions after different aging processes: (a) 150 °C, 4 h; (b) 150 °C, 8 h; (c) 150 °C, 12 h; (d) 175 °C, 4 h; (e) 175 °C, 8 h; (f) 175 °C, 12 h; (g) 200 °C, 4 h; (h) 200 °C, 8 h; (i) 200 °C, 12 h

Figure 4 shows the tensile curves of 6005A aluminium alloy extrusions in longitudinal direction after different aging processes. As seen from Figs. 4(a), (b) and (c), under the aging conditions of the same time and different temperatures, the curve profiles in the tensile yield, strengthening and necking stages are significantly different, but under the aging conditions of the same time and different temperature, as shown in Figs. 4(d), (e) and (f), the curve profiles are consistent with each other. When the aging temperature is 150 °C and 200 °C after aging for different times, the strength and ductility of the alloy extrusions are varied obviously, however, both of them are almost unchanged when the aging temperature is 175 °C, particularly in the 4−8 h aging time range.

Dependences of the RT tensile property parameters of the 6005A aluminum alloy extrusions on the aging time are summarized in Fig. 5. As shown in Fig. 5, at the aging temperature of 150 °C, with the increase of the aging time, the tensile and yield strength increases but the tensile elongation firstly increases and then decreases rapidly. At the aging temperature of 175 °C, however, the variations of the strength and elongation values are

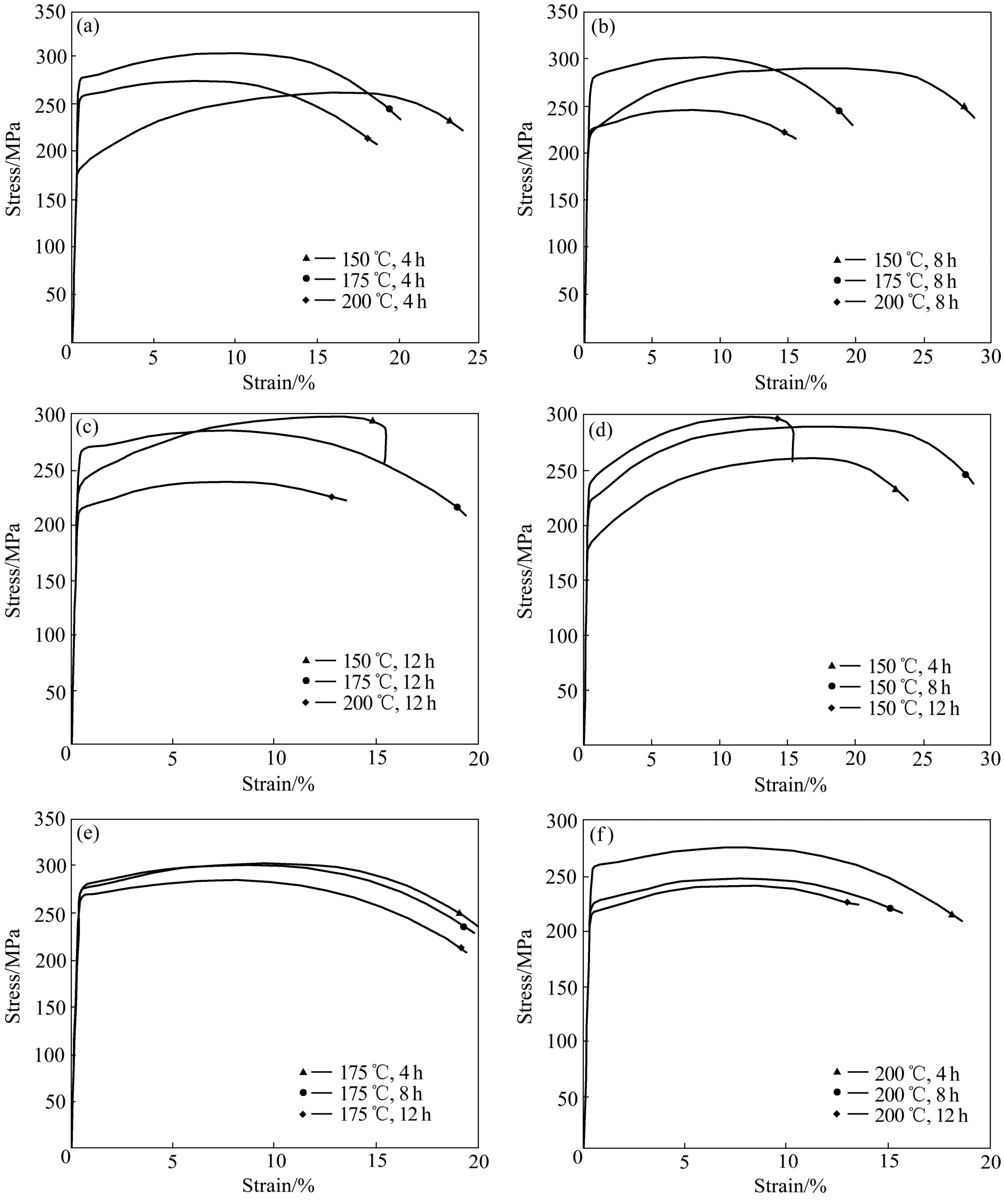

Fig. 4 RT tensile curves in longitudinal direction of 6005A aluminum alloy extrusions after different aging processes: (a) 150−200 °C, 4 h; (b) 150−200 °C, 8 h; (c) 150−200 °C, 12 h; (d) 150 °C, 4−12 h; (e) 175 °C, 4−12 h; (f) 200 °C, 4−12 h

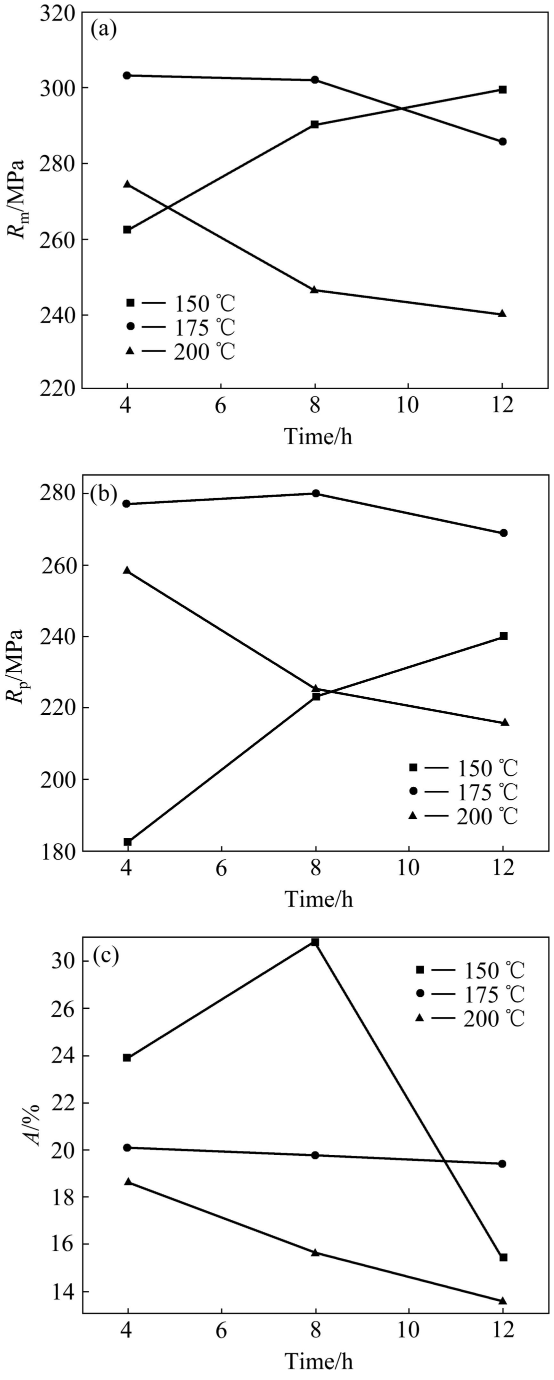

Fig. 5 Dependences of RT tensile property parameters of 6005A aluminum alloy extrusions on aging time at aging temperatures of 150, 175 and 200 °C: (a) Tensile strength R_m; (b) Yield strength R_p; (c) Tensile elongation *A*

within small ranges, and the strength has a declining trend after aging for more than 8 h. The tensile strength, yield strength and tensile elongation are all decreased with increase of the aging time at aging temperature of 200 °C.

Figure 6 shows the dependences of the RT tensile property parameters of the 6005A aluminum alloy extrusions on the aging temperatures. As can be seen from Fig. 6, at the aging temperature of 175 °C, the tensile and yield strength reach the maximum values more than 300 MPa and 270 MPa, respectively. The tensile elongation decreases with increase of aging temperature after aging for 4−8 h. When the aging time is 12 h, the yield strength and tensile elongation also reach maximum values at the aging temperature of 175 °C.

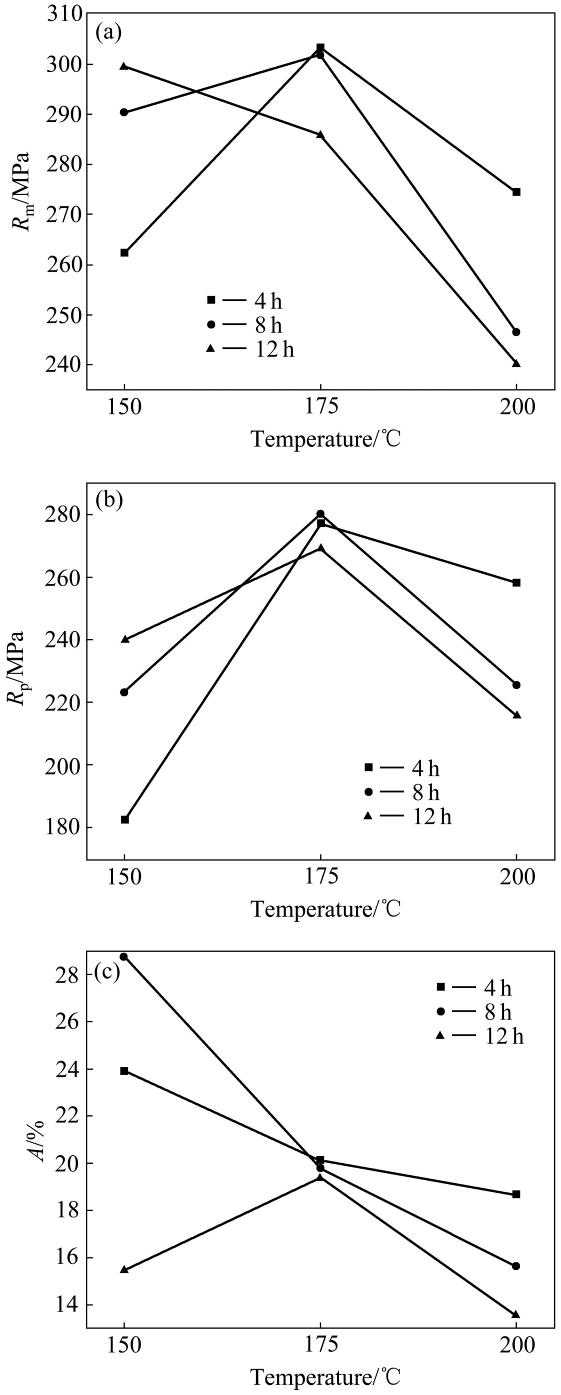

Fig. 6 Dependences of RT tensile property parameters of 6005A aluminum alloy extrusions on aging temperatures after aging times of 4, 8 and 12 h: (a) Tensile strength R_m; (b) Yield strength R_p; (c) Tensile elongation *A*

4 Discussion

Peak aging (T6) is one of the aging treatment methods extensively used in current industry application. The highest density of precipitations is produced in the matrix so that the highest strength of the alloys can be achieved. The aging kinetics is controlled by the diffusion of the solute atoms, which is strongly dependent on the temperature and time of the aging process. It is obvious that the precipitates should pay a very important role in the mechanical properties of 6005A aluminum alloys and the strengthening is always related with the type, interface, morphology, density and size of the precipitates. The coarse particles sized greater than 3 μm are usually formed in the extrusion process, which are consist of Fe-containing inclusions, such as AlFeSi and Al(Fe, Cr)Si [7,15]. As shown in Fig. 2, increasing with the time and temperature of aging, the size as well as the morphology of the coarse particles may be changed slightly by the thermal diffusion at the phase interface. The submicron precipitations should be produced in the aging process [16]. As indicated in Fig. 3, under the condition of short term aging process with a single stage, the quantity of the submicron precipitations primarily depends on the aging temperature and the size should be affected by the aging time.

The results show that the aging precipitation sequence of Al-Mg-Si series alloys can be described as supersaturated solid solution (SSS)→cluster→GP zones→metastable β''→metastable β'→stable β(Mg_2Si) [1,17,18]. The supersaturated solid solution is developed gradually to microstructures with the lowest energy in the aging process. However, in the form of phase equilibrium process, usually there will be some other metastable phase precipitations. Because of the stored energy during the extrusion process, when the temperature exceeds a certain threshold, the second phase easily nucleates and then grows up, especially at the grain boundary with relatively high energy. That may be the reason why the larger AlFeSi particles, as shown in Figs. 3(g)−(i), are precipitated at the grain boundaries at the aging temperature of 200 °C.

As displayed in Fig. 4, the profiles of tensile curves at each stage are obviously different at the different aging temperatures, but similar to that under condition of different aging times. These results suggest that RT mechanical properties of the extrusions are more sensitive to the aging temperature than to the aging time. Because the temperature parameter may affect the type and critical size of precipitated phase in the aging process, the tensile deformation process and mechanism may be different in the aged alloy. As indicated in Figs. 5 and 6, the alloy should be in over aging state after aging at 150 °C for 4−12 h. The better peak-aging strengthening effect reaches at 175 °C for 4−8 h, and the larger volume fraction of the submicron precipitations is also achieved under this condition, as shown in Fig. 3. The over-aged softening effect is presented at 200 °C, especially for the aging time more than 4 h.

The tensile elongation is mainly determined by the quantity and size of the precipitations. Due to the small size of aging precipitates, deformation dislocation easily cut the precipitates and the dislocation will continue to move along the channel, leading to the occurrence of deformation band, then the ductility of the alloy is reduced [7]. The coarse Al(Fe,Cr)Si precipitations are evolved from granular to rod-like particles, which are likely to cause stress concentration, especially when AlFeSi particles are formed at grain boundaries after aging at 200 °C. These particles can further reduce the strength and plasticity of the 6005A alloy extrusions.

5 Conclusions

1) In the aged microstructures of the extrusions, the morphologies of the coarse Al(Fe, Cr)Si particles formed in the extrusion process are evolved from granular to rod-like with increase of the aging temperature or the aging time. The volume fraction of the submicron precipitations reaches the maximum value at 175 °C. AlFeSi particles in size of 1−3 μm are precipitated at the grain boundaries at 200 °C.

2) Room temperature mechanical properties of the extrusions are more sensitive to the aging temperature than to the aging time. The optimum and stable mechanical properties are achieved when the aging procedure 175 °C, 4−8 h has been performed on the extrusions. The tensile strength and the yield strengths in the longitudinal direction of the aged extrusions are more than 300 MPa and 270 MPa, respectively.

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时效温度与时间对 6005A 铝合金挤压型材显微组织与力学性能的影响

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摘 要：研究时效时间和时效温度对 6005A 铝合金显微组织与力学性能的影响，对该铝合金挤压型材进行人工时效实验，时效时间分别为 4、8 和 12 h，时效温度分别为 150、175 和 200 °C。结果表明：随着时效温度和时间增加，挤压过程形成的粗大 Al(Fe, Cr)Si 析出相形貌由颗粒状向棒状转变，175 °C 时亚微米级析出相体积分数最大，200 °C 时在晶界析出 1~3 μm 左右的 AlFeSi 相。挤压型材的室温力学性能对时效工艺中的温度参数更加敏感，时效工艺为 175 °C，4~8 h 时具有最佳的强度和较稳定的力学性能，抗拉强度与屈服强度分别达到 300 MPa 和 270 MPa 以上。

关键词：6005A 铝合金；挤压；时效；Al(Fe,Cr)Si 颗粒；AlFeSi 颗粒；显微组织；力学性能

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