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Effects of aging in electric field on 2024 alloy①

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[Abstract] The effect of heat treatment in an electric field on micro-plastic deformation characteristics of 2024 Al alloy was investigated. The mechanism of aging in an electric field affecting the micro-plastic deformation behavior was preliminarily discussed. The results show that the resistance to micro-plastic deformation of the alloy can be greatly increased by aging in an electric field. Aging temperature, aging time and electric field strength are selected by adopting the orthogonal design method and the optimum technological parameters are obtained.

[Key words] 2024 Al alloy; aging; electric field; resistance to micro-plastic deformation
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1 INTRODUCTION

With the development of modern science and technology, the materials used in components of precision machinery, apparatus and instruments have been demanded for high dimensional stability. The study on micro-plastic deformation behavior of the materials is gradually emphasized and the resistance to micro-plastic deformation (microyield strength) of the materials becomes more important[1~7] because the micro-plastic deformation of the order of 10^{-6} or 10^{-7} for components may decrease the precision of instruments. At present time, many technologies such as aging, thermomechanical treatment, thermo-cold cycling treatment[8~10], are adopted in order to improve the resistance to micro-plastic deformation of the materials. Heat treatment in an electric field is a technology using new energy resource originated in 1960's. The previous study[11] proved that the yield strength of an Al-Li alloy can be increased by aging in an electric field, however the effect of heat treatment in an electric field on the microyield strength of 2024 Al alloy has not been reported. The micro-plastic deformation characteristics of 2024 Al alloy after aging in an electric field was investigated in this paper in consideration of the dimensional stability of 2024 Al alloy used for components of instruments. An attempt was made to understand the mechanism of the effect of strong electric field on the performance of 2024 Al alloy and a new effective and efficient dimensional stabilizing technique was selected.

2 EXPERIMENTAL

2024 Al alloy plate with 3 mm thickness was used. The tensile samples were cut from the plate and the longitudinal axis of them was parallel to the rolling direction of the plate. The gauge length of samples was 50 mm. Solid solution was performed at 495 ℃. $L_9(3^3)$ orthogonal design method was adopted for designing the parameters of aging process in an electric field. The factors and levels are shown in Table 1. The contrast experiment with or without the electric field during aging are proceeded as follows: 1) E = 0, 190 ℃, 10 h; 2) No. 8 technology shown in Table 1, i. e. E = 4 kV/cm, 190 ℃, 10 h. During aging in an electric field, a sample was used as positive electrode and a stainless plate was used as negative electrode. The samples, stainless plates and furnace body were isolated with glimmer so that the insulation was assured.

The tensile specimens were bonded double-faced by electrical resistance strain gages. In order to obtain the stress-residual strain curves and the microyield strength, a series of loading-unloading cycles were carried out on an INSTRON 1186 electronic tensile machine and the load was increased by 150 N for each cycle during tensile. The strain sensitivity attains to about 1×10^{-6}. An erratic current electric conductivity apparatus was used for measuring the electric conductivity of samples. Every performance data is the average value of three pieces.

3 RESULTS AND DISCUSSION

The stress-residual strain curves of 2024 Al alloy aged without electric field or aged in an electric field are shown in Fig. 1. It can be seen that the resistance to micro-plastic deformation of the alloy aged in an electric field of 2 kV/cm is great higher than that of the alloy aged without electric field. The stress corresponding to residual strain $\varepsilon_p = 1\times10^{-6}$ is defined as microyield strength (σ_{mys}). The microyield strength of the alloy aged at 190 ℃ for 10 h is only 115 MPa, however, the microyield strength of the alloy aged at 190 ℃ for 10 h in an electric field of 2 kV/cm is im-

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Table 1 Experimental procedures and microyield strength

Procedure number	Factor C, temperature / ℃	Factor B, time / h	Factor C, electric field strength / (kV·cm^{-1})	σ_{mys} / MPa
1	120	2	2	121.4
2	120	10	4	124.9
3	120	50	6	99.7
4	160	2	4	106.3
5	160	10	6	92.9
6	160	50	2	153.8
7	190	2	6	128.4
8	190	10	2	161.6
9	190	50	4	102.7
K_1	346	356.1	436.8	
K_2	353	379.4	333.9	
K_3	392.7	356.2	321	
$k_1 = K_1/3$	115.3	118.7	145.6	
$k_2 = K_2/2$	117.7	126.5	111.3	
$k_3 = K_3/3$	130.9	118.7	107	
Range R	15.6	7.8	38.6	
Optimum procedure	A_3	B_2	C_1	

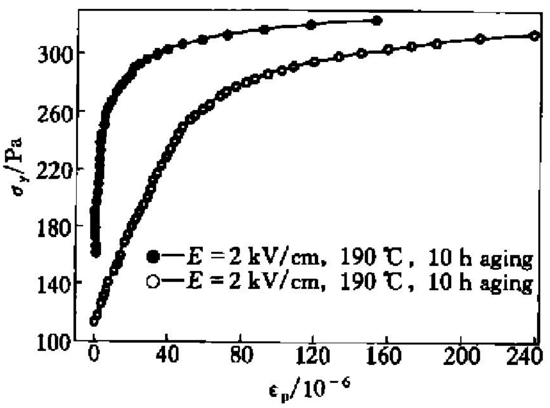

Fig. 1 Stress-residual strain curve of 2024 alloy aged

proved to 161 MPa. The amplitude of increment is 40%. When ε_p is not more than 1×10^{-5}, the larger the residual strain is, the more obvious the effect of the electric field on the microyield strength is. For example, when ε_p is 1×10^{-5}, the resistance to micro-plastic deformation is improved by 85%, and then the amplitude of increment gradually declines with ε_p increasing. Moreover, it can be known from Fig. 1 that the stress-residual strain curves of the alloy are divided to three stages after aging in an electric field or without electric field. The first stage is linear stage, and the strain exponent is very high. The second stage is a transient stage, and the strain exponent gradually decreases. The strain exponent of the third stage is very low and approaches constant. In the initial stage of micro-plastic deformation, the micro-hardening rate of the alloy aged in an electric field is higher than that of the alloy aged without electric field. This indicates that the dislocation movement mechanisms of 2024 Al alloy are different during two processes.

In order to obtain the greater resistance to micro-plastic deformation, the experimental procedure is designed according to the orthogonal design method, the procedure parameters and the obtained microyield strength from each process are shown in Table 1. The ranges corresponding to factor A (aging temperature), factor B (aging time) and factor C (electric field strength) are respectively $R_C > R_A > R_B$, so that when the levels of the three factors change, the order of importance of the effect on σ_{mys} is $C > A > B$, that is, the effect of changing the electric field strength on σ_{mys} is the most important, then the aging temperature and last the aging time.

The effects of three factors on microyield strength are shown in Fig. 2. The subsequences of microyield strength from high to low corresponding to different levels of each factor are $A_3 > A_2 > A_1$, $B_2 > B_1 = B_2$, $C_1 > C_2 > C_3$. Different levels of each factor are considered at the same time comprehensively, and the optimum procedure is determined as $A_3B_2C_1$, e.g., aging at 190 ℃ for 12 h in an electric field of 2 kV/cm, the maximum microyield strength is achieved.

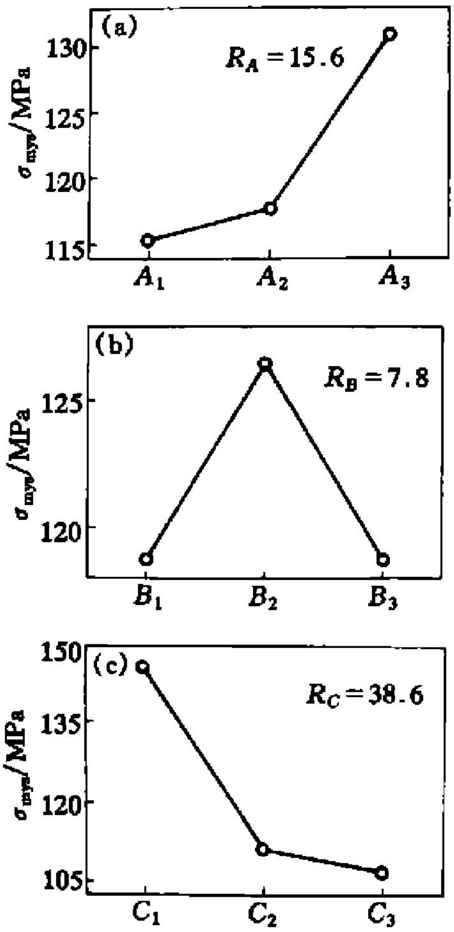

Fig. 2 Effects of each level on microyield strength

The experimental results show that the technology of aging in an electric field is an effective means to improve the resistance to micro-plastic deformation of the materials. Strong electric field has great effect on the micro-plastic deformation behavior of the materials, however the electric field strength from 2 kV/cm to 6 kV/cm exists an optimum value, that is 2 kV/cm. As aged at 190 ℃ for 10 h in a higher electric field of 8 kV/cm, the microyield strength of 2024 Al alloy also decreases.

In order to understand the mechanism of heat treatment in an electric field, the electric conductivity of some samples after heat treatment was measured. Electric conductivity can be expressed by the following equation[12]:

$$\sigma = \frac{1}{\rho} = \frac{ne^2\tau}{2m_e}$$

where σ is electric conductivity, ρ is electrical resistivity, n is free electron density of the metal, e is electron quantity of electricity, τ is average free time of free electron impaction, m_e is electron quality.

For the same metal, free electron density is constant and electric conductivity is proportional to average free time of electron impaction. That is to say that the electric conductivity depends the impaction frequency between free electron and barriers. The higher the impaction frequency and the shorter the free time, so that the electric conductivity becomes lower.

In metals, the barriers for electron movement include the thermal vibrating atoms near equilibrium position of crystal lattice, impurities and defects in the metals. So after treated by different technologies, the electric conductivity in materials may change depending on the solubility of solute atoms and the defect intensity of materials. Generally speaking, the higher the solubility of solute atoms and the defect intensity, the higher the impaction frequency and the shorter the average free time, thus the electric conductivity is lower in the alloy with high density of defects and high solubility of solutes.

The measuring results of electric conductivity and the microyield strength corresponding to each process are shown in Table 2. The lower electric conductivity of the specimens in underaged state, which are treated by No. 7 technology, may result from the higher solubility of solutes in matrix and the serious distortion in the crystal lattice. The specimens in peakaged state, which are treated by No. 8 or No. 10 technologies respectively, exhibit the higher electric conductivity due to the decrease of the solubility of the solutes in matrix. The specimens in overage state, which are treated by No. 9 technology, show the highest electric conductivity among the processes listed in Table 2. Comparing No. 8 with No. 10 technology, it can be found that the former's electric conductivity is slightly lower than the latter's. The reason may be that the higher solubility of solute atoms resulted from the aging treatment in an electric field which slightly depresses the aging in a certain extent, or may be that the defect intensity of the alloy is increased after aging. The mechanism of the improvement of the resistance to micro-plastic deformation of the alloy resulting from the electric field needs to be further studied.

Table 2 Electric conductivity and microyield strength

Technology	Electric conductivity / ($Ms \cdot m^{-1}$)	σ_{mys} / MPa
(7) E = 6 kV/cm, 190 ℃/2 h aging	18.64	128.4
(8) E = 2 kV/cm, 190 ℃/10 h aging	22.81	161.6
(9) E = 4 kV/cm, 190 ℃/50 h aging	22.66	102.7
(10) E = 0, 190 ℃/10 h aging	23.25	115.0

4 CONCLUSIONS

1) The micro-plastic deformation behavior of 2024 Al alloy changes and the micro-yield stress of the alloy increases during aging in an electric field.

2) By means of orthogonal design experiment, the optimum procedure availabel to 2024 Al alloy is achieved, that is $E = 2$ kV/cm, aging at 190 ℃ for 10 h. Treated by this technology, the resistance to micro-plastic deformation of the alloy can come up to 161 MPa, and it has an increase of 40% compared with that of the alloy treated by common aging process.

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