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ScienceDirect
Trans. Nonferrous Met. Soc. China 24(2014) 2067−2071
Transactions of Nonferrous Metals Society of China
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Precipitation orientation effect of 2124 aluminum alloy in creep aging

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Received 17 October 2013; accepted 23 April 2014

Abstract: The precipitation behaviors of 2124 aluminum alloy under the conditions of artificial aging (AA), creep aging (CA) and creep aging with pre-deformation (PCA) were investigated by means of mechanical property and microstructure. The results show that the mechanical properties of CA treated sample decrease significantly compared with AA treated sample. The yield strength of the CA treated sample falls by 14%, the tensile strength falls by 6.2%, and the elongation falls by 21%. Nevertheless, the mechanical properties of PCA sample are improved obviously, close to the AA treated sample. Moreover, the generation and control mechanisms of the precipitation orientation effect in 2124 aluminum alloy were studied. It is deduced that the key mechanism lies in the effect of dislocation.

Key words: 2124 aluminum alloy; creep aging; orientation effect; dislocation

1 Introduction

The creep age forming (CAF) technology of aluminum alloy, which utilizes the coexistence of the creep forming and the age strengthening ingeniously, has been adopted as a collaborative manufacturing method of deformation and property [1,2]. Examples of creep age forming application include the upper wing skins of Gulfstream IV/V, B-1B long-range combat aircraft and Airbus A330/340/380 manufactured by Textron as well as the Hawk upper skin produced by British Aerospace [3−5]. Moreover, it still has great potential applications in future aircraft and aerospace industry.

Quite a few recent reports indicated that [6−11] the precipitates show a directional distribution under the applied stress in the aging process of some aluminum alloys (such as Al−Cu alloy, Al−Cu−Mg alloy). It can be called as ‘precipitation orientation effect’. Because this effect causes the degraded material property of aluminum alloy [6,7], the application of the CAF technology has been limited in Al−Cu(−Mg) alloys. Therefore, it will be of important significance to ascertain the mechanisms of the orientation effect and the control methods.

It must be noted that, for Al−Cu−Mg alloys, not all the process conditions can cause obvious property reduction. For example, the degraded material property is only 3%−5% in the conditions of Ref. [8]. However, based on our previous research results [12], the clear property reduction may appear in the range of creep stress of 150−260 MPa. And the lowest point of the room-temperature mechanical property exists near 200 MPa, with the heat treatment regime T6 (the solid solution treated and quenched samples were aged at 463 K for 12 h).

The aim of this study is to investigate the precipitation behavior of 2124 alloy in creep aging. Based on three different test conditions, including the artificial aging, the creep aging and the creep aging with pre-deformation, the material property and microstructure of these samples were measured and compared to study the precipitation behavior and the mechanisms of the orientation effect.

Foundation item: Projects (2010CB731700, 2012CB619500) supported by the National Basic Research Program of China; Project (51375503) supported by the National Natural Science Foundation of China
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DOI: 10.1016/S1003-6326(14)63313-6

2 Experimental

Hot rolled plates of 2124 aluminum alloy with 5 mm in thickness were used in the experiments, and the chemical composition is presented in Table 1. The specimens were machined in rolling direction and the dimensions are shown in Fig. 1. After being solution treated (768 K, 40 min) and water quenched, the specimens were divided into three sets: the first set was treated by artificial aging at 463 K for 12 h (denoted as AA); the second set was treated by creep aging at 200 MPa, 463 K for 12 h (denoted as CA); the third set was treated by 6% pre-deformation, and then creep aging at 200 MPa, 463 K for 12 h (denoted as PCA). Creep aging experiments were carried out on a RWS50 type electronic creep relaxation test machine with heat equipment. The specimen was fitted and aligned in the middle of the furnace; when the temperature became steady in a short time, a load was applied and the elongation of the specimen was measured. Tensile tests in the rolling direction were carried out at room temperature using the CSS-44100 machine operating at a constant crosshead speed of 2 mm/min. Transmission electron microscopy (TEM) was used to characterize the precipitates in different conditions. Samples for TEM were mechanically thinned down to 80 μm and twin-jet electropolished in a solution of 30% nitric acid and 70% methanol (in volume) at approximately 243 K. Then the TEM specimens were observed by a TECNAL G220 transmission electron microscope operating at 200 kV.

Table 1 Chemical composition of 2124 alloy (mass fraction, %)

Cu	Mg	Mn	Ti	Zn	Cr	Fe	Si	Al
4.18	1.46	0.52	0.15	0.25	0.1	0.3	0.2	Bal.

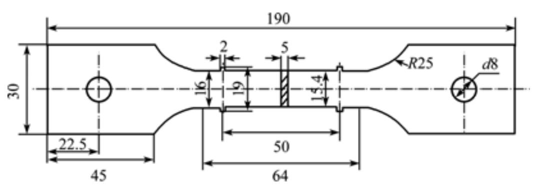

Fig. 1 Specimen geometry in creep test (unit: mm)

3 Results and discussion

3.1 Mechanical property

Measured results of the room-temperature mechanical properties of the three sets of samples are shown in Fig. 2. It can be seen that, the mechanical properties of the creep aged sample decrease significantly compared with artificial aged sample. The yield strength of the creep aged sample falls by 14%, the tensile strength falls by 6.2%, and the elongation falls by 21%. Nevertheless, for the PCA treated sample, which was treated by pre-deformation before creep aging process, the yield strength and the tensile strength are improved obviously, close to the AA treated sample. Besides, the elongation is comparable to the CA sample, with slightly reduction.

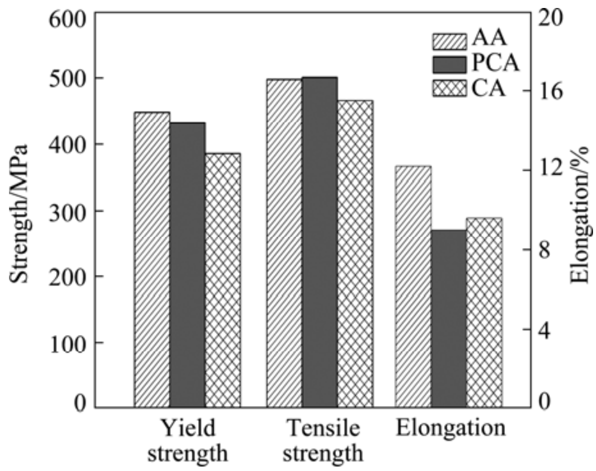

Fig. 2 Measured mechanical properties of 2124 Al alloy samples after artificial aging (AA), creep aging (CA) and creep aging with pre-deformation (PCA)

3.2 Microstructure

Figure 3 shows the TEM micrographs of 2124 Al alloy samples in the three kinds of test conditions. It is clear that the precipitation distribution of the CA treated sample appears very different in the crossed shape from AA treated sample (Fig. 3(a)), but these precipitates show oriented distribution pattern obviously. The reason for the degraded material property of 2124 aluminum alloy samples in Section 3.1, according to the research results of ZHU et al [6,9,13], can be ascribed to the precipitation orientation effect. The TEM micrograph of the PCA treated sample, which has a pre-deformation of 6% before the creep aging process, is shown in Fig. 3(c). It can be observed that the distribution pattern of the precipitates recovers to the crossed shape, and the oriented distribution in creep aging process has been controlled.

Figure 4 shows the selected area electrical diffraction (SAED) patterns of the samples in AA, CA, and PCA test conditions. For 2X24 aluminum alloys, the mass ratio of Cu to Mg ranges from 2.1 to 4. It can be known from the Al−Cu−Mg alloy phase diagram that the main strengthening phase is the disk-shaped Al_2CuMg phase [14], which has been reported to precipitate in plate-shape with the $\{120\}_{Al}$ habit planes elongated along the $[100]_{Al}$ direction [15]; the general precipitation sequence during the aging is represented as [16,17]: supersaturated solid solution (SSSS) → Cu−Mg co-clusters (GPB zone) → S''/S' → S'/S (Al_2CuMg).

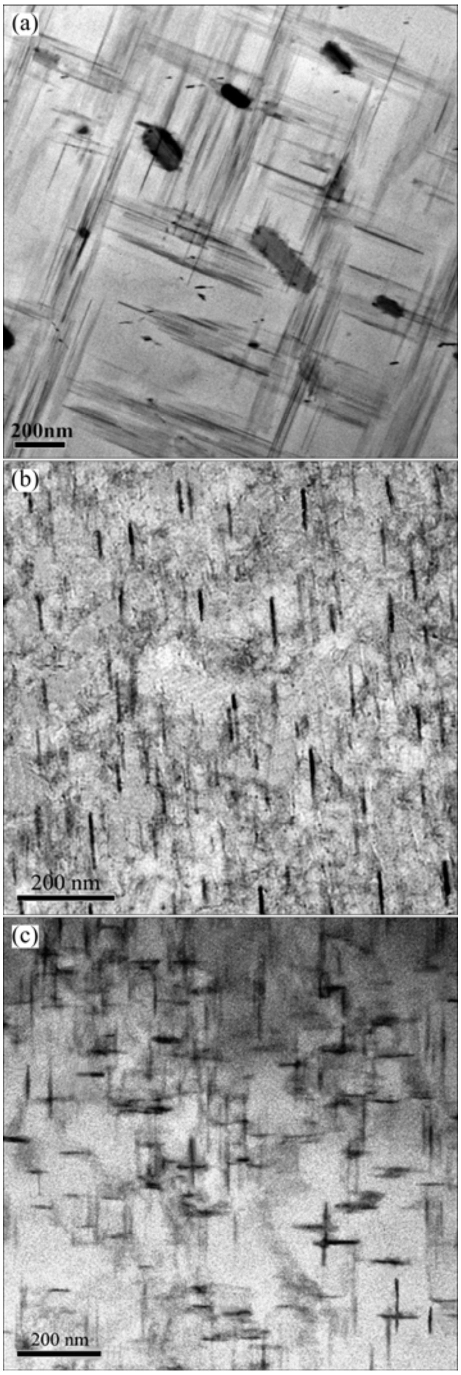

Fig. 3 TEM micrographs of 2124 aluminum alloy samples in different test conditions: (a) Artificial aging (AA); (b) Creep aging (CA); (c) Creep aging with pre-deformation (PCA)

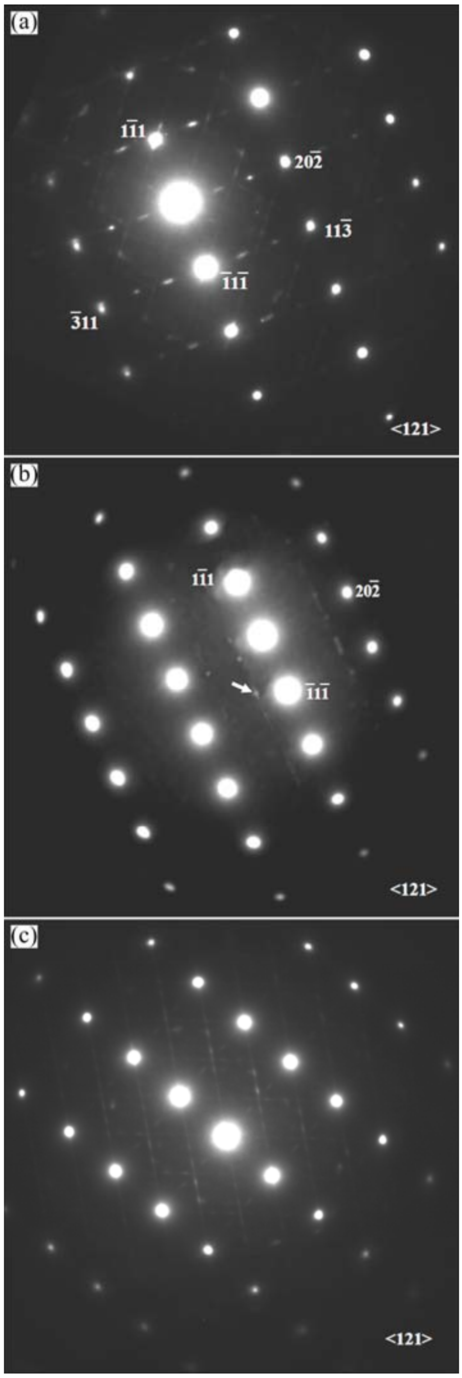

Fig. 4 SAED patterns of 2124 aluminum alloy samples in different test conditions: (a) Artificial aging (AA); (b) Creep aging (CA); (c) Creep aging with pre-deformation (PCA)

In Fig. 4(a), it can be observed that, the square cross stripes, which are consistent with the reported results of S' phase in Ref. [15,18], exist in the diffraction pattern. The diffraction fringes and spots, which almost have the same intrinsic brightness, lay along the two vertical directions of $(\bar{2}10)$ and $(0\bar{1}2)$. And this corresponds to the cross-shaped precipitates in AA treated sample, as shown in Fig. 3(a). In Fig. 4(b), the diffraction fringes almost entirely distribute at $1/3(20\bar{2})$ or $2/3(20\bar{2})$ and parallel to $(1\bar{1}1)$ direction, as indicated by the arrow. It can thus be known that the directional precipitation arises in the CA treated sample, meanwhile, precipitation along the vertical direction is restrained. So, the TEM micrograph of CA treated sample shows the oriented distribution pattern, which is called as precipitation orientation effect. The SAED pattern of PCA sample is shown in Fig. 4(c), it can be seen that clear diffraction fringes lay along the two vertical directions of $(\bar{2}10)$

and $(0\bar{1}2)$, which is similar to the pattern of AA treated sample shown in Fig. 4(a). Therefore, the pre-deformation process can effectively control the oriented effect caused by the directional creep stress, which improves the strengthening effect significantly.

3.3 Discussion

In initial period of the creep aging, apparent dislocation lines can be observed around the coarse particles (*T* phase), as shown in Fig. 5(a). And then, the nucleation and precipitation preferentially take place in these dislocation lines, as shown in Fig. 5(b).

According to the research results of CAHN [19], when the nucleation occurs in the dislocation line, the change of the system free energy is

$$\Delta G = -A\ln r + 2\pi r\sigma + \pi r^2 \Delta G_V \quad (1)$$

where r is the nucleus radius; σ is the interfacial energy per unit area; ΔG_V is the volume free energy difference between the new phase and the parent phase; A is a material parameter related to dislocation.

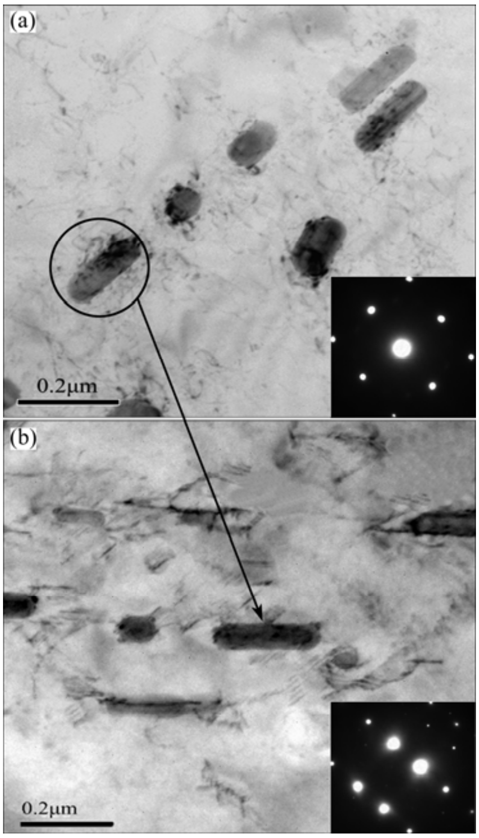

Fig. 5 TEM micrographs of 2124 aluminum alloy after CA in initial period of aging: (a) 0.5 h; (b) 2 h

In Eq. (1), the first factor, which expresses the change of the dislocation strain energy before and after the nucleation, is a negative value. Besides, ΔG_v in the third factor is also negative. Thus, the dislocation lines can be advantageous to the nucleation of precipitates.

If $\partial \Delta G / \partial r = 0$, then we can get the critical nucleus radius as follows:

$$r_k = \frac{\sigma}{2\Delta G_V}\left(1 \pm \sqrt{\frac{1+2A\Delta G_V}{\pi\sigma^2}}\right) \quad (2)$$

When $\left|\frac{2A\Delta G_V}{\pi\sigma^2}\right| > 1$, it means large $|\Delta G_V|$ but small σ; there is no critical nucleus radius and nucleation barrier, any atomic group can become a nucleus. Conversely, when $\left|\frac{2A\Delta G_V}{\pi\sigma^2}\right| < 1$, it means small $|\Delta G_V|$ but large σ; the precipitates are general in plate/disc-shape in this case, and the critical nucleus radius exists. In other words, the nucleation and precipitation of the plate/disc-shaped precipitates are easier to be affected by the dislocation lines.

Based on the analysis above, it is reasonable to deduce that the key mechanism of the generation and control of the oriented effect in 2124 aluminum alloy lies in the effect of dislocation. First of all, the distribution of the main strengthening phase (*S'* phase) appears cross shape in the artificial aging process of the 2124 aluminum alloy. But in the creep aging process, when the directional creep stress has been applied, according to the Schmid law [20], the dislocation will generate in a certain critical direction. At this point, because the low free energy in the dislocation lines contributes to the nucleation of the precipitates, the precipitates preferentially nucleate in the {210} plane, which is intersectant to the dislocation starting plane {111}. Meanwhile, the nucleation in the other vertical {210} plane has been restrained, so the oriented effect of the precipitates is induced. However, when the pre-deformation has been conducted before the creep aging process, because the deformation can produce dislocation, the Schmid law is no longer applicable when the directional creep stress is applied. In this case, the nucleation and growth of the precipitates no longer have the orientation, so the precipitation distribution returns to the cross shape.

4 Conclusions

1) The precipitation orientation effect, which arises in creep aging of 2124 aluminum alloy, causes severe property reduction.

2) Proper pre-deformation before the creep aging process can control the precipitation orientation effect in 2124 aluminum alloy, as well as improving the mechanical property.

3) The key mechanism of the generation and control of the precipitation orientation effect in 2124 aluminum alloy lies in the effect of dislocation.

References

[1] JEUNECHAMPS P P, HO K C, LIN J, PONTHOTA J P, DEANB T A. A closed form technique to predict springback in creep age-forming [J]. International Journal of Mechanical Sciences, 2006, 48(6): 621−629.
[2] ZHAN L H, LIN J G, DEAN T A. A review of the development of creep age forming: Experimentation, modelling and applications [J]. International Journal of Machine Tools and Manufacture, 2011, 51(1): 1−17.
[3] ADACHI T, KIMURA S, NAGAYAMA T, TAKEHISA H, SHIMANUKI M. Age forming technology for aircraft wing skin [J]. Materials Forum, 2004, 28: 202−207.
[4] HO K C, LIN J, DEAN T A. Constitutive modelling of primary creep for age forming an aluminium alloy [J]. Journal of Materials Processing Technology, 2004, 153: 122−127.
[5] ZENG Yuan-song, HUANG Xia, HUANG Shuo. The research situation and the developing tendency of creep age forming technology [J]. Journal of Plasticity Engineering, 2008, 15(3): 1−8. (in Chinese)
[6] ZHU A W, STARKE E A. Stress aging of Al−*x*Cu alloys: Experiment [J]. Acta Materialia, 2001, 49(1): 2285−2295.
[7] CHEN Yu-qiang, YI Dan-qing, PAN Su-ping, HUANG Xia, WANG Bin, ZHUO Ming-zhe. Effect of temperature on creep behavior of 2024 aluminum alloy [J]. The Chinese Journal of Nonferrous Metals, 2010, 20(4): 632−639. (in Chinese)
[8] ZHANG J, DENG Y L, LI S Y, CHEN Z Y, ZHANG X M. Effect of age-forming on microstructures and properties of 2324 Al alloy [J]. Transactions of Nonferrous Metals Society of China, 2013, 23(7): 1922−1929.
[9] ZHU A W, CHEN J, STARKE E A. Precipitation strengthening of stress-aged Al−*x*Cu alloys [J]. Acta Materialia, 2000, 48(9): 2239−2246.
[10] BAKAVOS D, PRANGNELL P B. A comparison of the effects of age forming on the precipitation behavior in 2xxx, 6xxx and 7xxx aerospace alloys [J]. Materials Forum, 2004, 28: 124−131.
[11] CHEN D Q, ZHENG Z Q, LI S C, CHEN Z G, LIU Z Y. Effect of external stress on the growth of precipitates in Al−Cu and Al−Cu−Mg−Ag alloys [J]. Acta Metallurgica Sinica, 2004, 40(8): 799−804.
[12] DENG Yun-lai, ZHOU Liang, JIN Kun, ZHANG Xing-ming. Microstructure and properties of creep aged 2124 aluminum alloy [J]. The Chinese Journal of Nonferrous Metals, 2010, 20(11): 2106−2111. (in Chinese)
[13] ZHU A W, STARKE E A. Strengthening effect of unshearable particles of finite size: A computer experimental study [J]. Acta Materialia, 1999, 47(11): 3263−3269.
[14] HUANG B Y, LI C G, SHI L K, QIU G Z, ZUO T Y. China Materials Engineering Manual (Volume 4) [M]. Beijing: Chemical Industry Press, 2006: 58. (in Chinese)
[15] WANG S C, STARINK M J. Two types of *S* phase precipitates in Al−Cu−Mg alloys [J]. Acta Materialia, 2007, 55(3): 933−941.
[16] MUTHU K S. Evaluation of precipitation reaction in 2024 Al−Cu alloy through ultrasonic parameters [J]. Materials Science and Engineering A, 2011, 528(12): 4152−4158.
[17] BADINI C, MARINO F, VERNÉ E. Calorimetric study on precipitation path in 2024 alloy and its SiC composite [J]. Materials Science and Engineering A, 1995, 191(1−2): 185−191.
[18] SHIH H C, HO N J, HUANG J C. Precipitation behaviors in Al−Cu−Mg and 2024 aluminum alloys [J]. Metallurgical and Materials Transactions A, 1996, 27(9): 2479−2494.
[19] CAHN J W. Nucleation on dislocations [J]. Acta Metallurgica, 1957, 5(3): 169−172.
[20] SCHMID E, BOAS W. Kristallplastizität [J]. Struktur and Eigenschaften der Materie, 1935, 17: 15−24.

2124 铝合金蠕变时效中的析出位向效应

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摘 要：针对 2124 铝合金在人工时效、蠕变时效和预变形后蠕变时效 3 种不同状态下的力学性能与微观组织，研究了强化相的析出行为。结果表明，蠕变时效试样的力学性能比人工时效试样的明显下降，其中屈服强度下降了 14%，抗拉强度下降了 6.2%，伸长率下降了 21%。而有形变的蠕变时效试样的力学性能则有明显改善，并接近人工时效试样的。此外，研究了 2124 铝合金蠕变时效过程中析出位向效应的形成与抑制机理，其关键在于位错的影响。

关键词：2124 铝合金；蠕变时效；位向效应；位错

(Edited by Hua YANG)