Study on the microstructure of 2124 aluminum alloy subjected to stress assisted aging

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Abstract. The effect of a load on the microstructure of 2124 aluminum alloy was investigated by employing transmission electron microscopy. When the alloy was aged at 190°C under a load of 6.05 kg, the deformation was increased with the aging time prolonging. Meanwhile the length of Al2CuMg(S) phase was shorter than the length of S phase in the alloy without loading. At the same time, there was no preferential orientation effect on S phase or Genier Preston Bugaryatsky (GPB) zones.

1. Introduction

The wing of airplane is commonly formed by bend forming with a load applying on aluminum alloy [1]. The bend forming has been applied for the manufacture of B-1B long range combat aircraft, A330/340 and A380 [2]. The load is in the range of elastic stress and applied during the aging process. It is necessary to understand the effect of load on the microstructure and properties. The effect of stress on the microstructure has been investigated by some researchers [3-9]. The precipitates in Al-Cu alloy and Al-Cu-Mg-Ag alloy show preferential orientation under an elastic stress during aging treatment. The mechanism of the orientation effect of 0° phase and Ω phase was explained by Eshelby elastic inclusion theory [5,10,11]. However the bend forming of 2124 aluminum alloy has not been studied. 2124 aluminum alloy is widely applied for the manufacture of the wing and fuselage of airplane. It is generally regarded that the main strengthening second phases in 2124 alloy are GPB zones and S phase. GPB zones are short range ordered phase with several nanometers. S phase is lath with crystal lattice parameters a=0.400 nm, b=0.923 nm, c=0.714 nm [12]. And there are 12 variants of S phases. The orientation effect of GPB and S phase is not clear up to now. It is essential to investigate the effect of load on the microstructure of 2124 aluminum alloys. Therefore, in this paper the microstructure and formability of 2124 aluminum alloy under loading condition was investigated.

2. Experimental methods

Table 1 shows the chemical composition of commercial 2124 aluminum alloy used in this paper. The dimension of the specimens is 260 mm×25 mm×2 mm. Bend forming experiment was carried out in a self-made furnace. The specimens were solution treated at 495°C for 1h and quenched into water at room-temperature. And then the specimens were immediately transferred into the furnace and aged at 190°C with a load of 6.05 kg. Vickers hardness was tested with 450SVDTM with a load of 5 kg and dwell...
time of 20 s. Thin foils for transmission electron microscopy (TEM) were prepared by cutting, grinding and punching into 3 mm discs. Electro-polishing was employed in a twin-jet Tenupol by a 33% nitric acid solution in methanol operated at -25°C and 13.8 V. FEI CM20 operated at 200kV was carried out to observe the microstructures.

Table 1. Chemical composition of commercial 2124 alloy (wt%).

|    | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  | Al  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|    | 0.08| 0.16| 4.31| 0.65| 1.51| 0.01| 0.02| 0.01| balance |

3. Results and discussion

3.1. The deformation mechanism

3-point bending was adopted to study the bending formation of 2124 aluminum alloy. The middle part of the specimen showed the largest deformation of the specimen. It can be calculated that the maximum stress of the specimen was 231 MPa when the load is 6.05 kg. This is lower than the yield strength 280 MPa of this alloy.

Figure 1 illustrates the relationship of the deformation and the aging time. It can be clearly seen that the deformation increases with the time prolonging. At the initial stage, the deformation gradually increases. But it increases rapidly at higher temperature. This can be explained by the creep mechanism with Arrhenius equation as shown in equation (1).

$$\varepsilon = A \sigma^n \exp \left( -\frac{Q}{RT} \right)$$  \hspace{1cm} (1)

Q is the activation energy; R is the gas constant; T is the absolute temperature. Higher temperature leads to larger deformation according to the equation (1). Therefore the deformation mechanism can be explained by creep mechanism.

![Figure 1](image1.png)

**Figure 1.** The change of deformation curves of 2124 alloy in bend-form.

![Figure 2](image2.png)

**Figure 2.** Ageing hardness curves of 2124 alloy aged at 190°C.

3.2. The mechanical properties of the alloy

The aging curve of 2124 alloy aged at 190°C is shown in figure 2. The peak aging time is 12h for the bend formed 2124 alloy. And the peak hardness is 142VHN, which is higher than 134VHN of the alloy that without a load.

3.3. The microstructure of the bend formed alloy

As discussed above, the largest deformation part is the half length of the specimen. It suffers a tensile
stress downside of the specimen and a compressive stress on the top of the specimen. The microstructure of the alloy aged to peak temper with and without a load is shown in figure 3. S phases and GPB zones are the predominant phases in the peak-aged 2124 aluminum alloy. When the alloy is aged without a load seen in figure 3(a), the length of S phase is 445 nm, which is longer compared to the length of 405 nm in the alloy with a load of 6.05 kg as shown in figure 4. This means the average length of S phases is shorter under the role of load, which can be explained by the vacancies. Quantities of vacancies generate when the alloy is solution treated and quenched [13]. As a load is applied, on one hand, dislocations are generated which can increase the nucleation sites for the second phases. On the other hand, lots of vacancies will migrate to the dislocations which lead to the concentration of vacancies decreasing. The growth of second phase will be retarded due to the decreasing of the vacancies. Therefore the applying load can affect the growth of S phase and decrease the length of S phase.

![Figure 3](image1.png)

**Figure 3.** Bright field images and corresponding SAD pattern of S phases in 2124 Al alloy aged at 190°C for 12h. B=[001] (a) without load (b) with load of 6.05 kg.

![Figure 4](image2.png)

**Figure 4.** The number fraction and the dimension distribution of S phases.

It can be seen that the S phases are in large dimensions and distribute equivalently on all {210} planes in the aged alloy without a load. Meanwhile, S phases are also growing equivalently on different directions when the alloy subjected a load of 6.05 kg as shown in figure 3(b). The load has no obvious effect on the distribution of S phases. This can be also proved by selected area diffraction pat-
terns (SAD). The intensity of the reflection spots of S phases is the same in [200]_α, [020]_α directions, which means that the quantity of S phases along [200]_α, [020]_α are the same. This indicates that load has little role on the orientation of S phases.

GPB zones play a dominant role on strengthening the alloy [14, 15]. Many tiny needle GPB zones distribute homogeneously in the alloy as seen in figure 5. The dot pattern phases in the figure 5 are the cross-section of GPB zones. It indicates that the number density of GPB zones is almost the same with or without stress. In the magnified images (figure 6), it can be also clearly seen that dimension of the cross-section of GPB zones has no significant difference. Additionally, the SAD pattern agrees with this finding. And the strength and morphology of the streaks along [200]_α, [020]_α are almost the same with or without a load. As a result the load has no effect on GPB zones.

![Figure 5](image1.png)

**Figure 5.** Bright field images and corresponding SAD pattern of GPB zones in 2124 Al alloy aged at 190℃ for 12h. B=[001] (a) without load (b) with load of 6.05 kg.

![Figure 6](image2.png)

**Figure 6.** High magnification of GPB zones in 2124 Al alloy aged at 190℃ for 12h (a) without a load (b) with a load of 6.05 kg. B=[001].

In the previous studies, several models of GPB zone by other researchers are proposed [16-18], among which GPB proposed by Kovarik is adopted in this paper [18]. The orientation relationship of the GPBII zone with the matrix is [100]_Al/[100]_GPBII and [010]_Al/[010]_GPBII. It is known that GPB zones possess an orthorhombic lattice and space group Cmmm. There are three kinds of variants of GPB zones. One of the variants is parallel to the incident beam, while the other two are perpendicular to it. So the two variants are observed to study the effect of external load. When applying a load, the forming energy can be expressed by phase transformation strain and the uniform strain derived from
external load. Due to the structure of GPB zones are symmetrical, the uniform strain can be considered as a constant. Then the transformation strain is essential for the total energy. It can be expressed as equation (2). Variant 1 and variant 3 can be simplified as equation (3).

\[
\varepsilon_{ij} = \begin{pmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{pmatrix} = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} \\ \varepsilon_{yx} & \varepsilon_{yy} \end{pmatrix}
\]

(2)

\[
\varepsilon^0(1) = \begin{pmatrix} \varepsilon_3 & 0 \\ 0 & \varepsilon_1 \end{pmatrix}, \quad \varepsilon^0(3) = \begin{pmatrix} \varepsilon_1 & 0 \\ 0 & \varepsilon_3 \end{pmatrix}
\]

(3)

Where \( \varepsilon_1 = \frac{ma - na}{na} \), \( \varepsilon_3 = \frac{c - a}{a} \), the atomic parameter of Al \( a_0 = 0.405 \) nm. Assuming the ratio of precipitate atom and the matrix atom is 1:3. Then it can be calculated \( \varepsilon_1 = -0.25\% \), \( \varepsilon_3 = -0.25\% \), and \( \varepsilon^0(1) \) is equal to \( \varepsilon^0(3) \). Therefore the total energy is the same for different variants, which means the load has no obvious effect on the GPB zones.

The crystal structure of S phase is orthogonal with the crystal parameters \( a = 0.400 \) nm, \( b = 0.923 \) nm, \( c = 0.714 \) nm, and the orientation relationship with the matrix is \([100]_\text{Al} // [100]_\text{S}, [02\bar{1}]_\text{Al} // [010]_\text{S}, [012]_\text{Al} // [100]_\text{S}\) [19,20]. The misfit can be calculated by the equation as following:

\[
\delta_i = \frac{md_p - nd_{Al}}{nd_{Al}}
\]

(4)

Where \( d_p \) is the lattice parameter of precipitate, and \( d_{Al} \) is the lattice parameter of aluminum. The results are as shown in table 2. The misfit of \( a \) axis is small, so that the interface energy to form the plane perpendicular to \( a \) axis is very small. Moreover the number of matching lattices is 1. S phase is coherent with Al matrix along \( a \) axis, which means S phases are easy to grow along \( a \) axis. However, when the number of Al planes is up to 5 and 4 for \( b \) and \( c \) axis respectively, the misfit can reach to the minimum value. In this case, due to the number of Al planes is large, it is difficult to grow fast along \( b \) and \( c \) axis. Therefore, the morphology of S phase is lath. When applying a load on the alloy, S phases suffer strain energy and interface energy. Strain energy is quite small compared to interface energy. Consequently, as for part-coherent and incoherent S phase, the external load has no effect on S phases.

| Planes       | Al plane space (nm) | S phase space (nm) | \( \delta \) (%) |
|--------------|---------------------|--------------------|-----------------|
| (100)\text{Al} // (100)\text{S} | \( d_{100}=0.405 \) | 0.400 | +1.23 |
| (012)\text{Al} // (010)\text{S} | \( d_{012}=0.1811 \) | 0.923 | -1.93 |
| (02\bar{1})\text{Al} // (001)\text{S} | \( d_{02\bar{1}}=0.1811 \) | 0.714 | +1.44 |

4.Conclusions

In this work, the effect of a load on the 2124 aluminum alloy during aging process was studied. And mechanical properties and microstructure of 2124 alloy were investigated. When the alloy was aged at
190°C under a load of 6.05 kg, the deformation was increased with the aging time prolonging. Due to the increased nucleation sites and decreased vacancies by introduction of a load, the length of the S phases was shorter in the bended alloy compared with the reference alloy without loading. However the load has no obvious effect on the preferential orientation of S phase or GPB zones because the total energy of different variants of S phases or GPB zones is almost the same.

Acknowledgments
The authors are greatly thankful to the financial support from the “Fundamental Research Funds for the Central Universities” (N172304047) and the Natural Science Foundation of Hebei Province in China (E2018501088 and E2018501030).

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