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ARTICLE

Effect of Natural Aging Time on Tensile Properties and Fracture of Heat-treated AA2024-O Al-alloy

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Abstract: The effect of natural aging time on tensile properties and fracture of the heat-treated AA2024-O Al-alloy was investigated. The stress-strain curves, the yield strength and the tensile strength of the specimens with different natural aging time were obtained by tensile test at room temperature. The constitutive equation that could predict the stress was established. The effect of natural aging time on the material microstructure was also analyzed by observing the fracture. The results of the experiment demonstrate that the specimens are gradually strengthened to a certain point, and then the yield stress and the ultimate tensile strength are decreased until the material reaches a stable state. There are many dimples distributed on the fracture surface that was observed by SEM, so the fracture surfaces are thought to be a ductile fracture. Despite natural aging during long periods, the dimples become fewer and the plasticity worsened. A series of phenomenological functions are presented for establishing the constitutive equation of AA2024-O Al-alloy strengthened. The model can predict the stress of the naturally aged material.

Key words: AA2024; natural aging; aging strengthening; fracture

The commercial Al-Cu-Mg (AA2024) aluminum alloy is widely applied to the aviation industry for the fabrication of structural components, including fuselage frame, fuselage skin, frame, wing skin, wing rib and tail[1-3].

AA2024 contains copper, magnesium, manganese and some minor alloy elements with a complicated microstructure. This material is composed of plentiful different intermetallic particles. It is widely accepted that AA2024 is strengthened by precipitating the microstructure during the natural aging period.

Aluminum alloy 2024 is a kind of high strength and low density alloy to mass ratio. Its favorable mechanical properties are acquired owing to aging or precipitation strengthening. However, it is difficult to manufacture these parts in the final temper.

It is well known that despite natural aging during short periods, the aluminum alloys heat-treated are soft and plastic, so that they are conducive to plastic forming. Taking advantage of the properties, the aluminum alloys are generally solution heat treated, stored in a freezer to arrest the aging process and then formed in the “as-quenched” (W-temper) condition[4]. The "as-quenched" process is applied to rubber bladder forming for stamping the complex structure sheet metal parts in the field of aviation[1,5-7]. It is demonstrated that the aging of 2xxx series of alloys is finished in 96 h[4]. The evolution of yield stress and ultimate tensile stress are increased in 96 h. The aluminum alloy is maintained at room temperature for several days, which is designed for the alloy to age originally (natural aging or equivalent T3 and T4 treatments).

The values of strength and hardness increase obviously, due to precipitating the new phase from the supersaturated solid solution[8]. So it is necessary to observe the microstructure and the development tendency of the AA2024 to grasp the rules of organizational evolution.

For Cu/Mg ratio between 4 and 8, both θ-phase(Al_2Cu) and S-phase(Al_2CuMg) equilibrium phases form in the precipitation sequence[3]. The phase transition occurs between

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the solid solution treatment of aluminum alloy and the formation of stable phase.

There are two forms of precipitation during aging after a solution heat treatment and quenching. The sequences of possible precipitations of the Al-Cu-Mg alloys follow the following steps:

Supersaturated solid solution (SSS)→GPzone→θ''→θ'→θ (Al_2Cu)

Supersaturated solid solution (SSS)→GPBzone→S''→S'→S (Al_2CuMg)

GP and GPB stand for Guinier-Preston and Guinier-Preston-Bagaryatsky, respectively. GP and GPB form in the initial stage of aging treatment and are coherent with Al matrix, which are regarded as a short range ordering of Cu and Mg solute atoms. The θ'' and S'' are very small precipitates and almost coherent with Al matrix. The θ' and S' are usually seen as semi-coherent with the matrix, whose structures are similar to those of the equilibrium θ and S phase, with slightly different lattice parameters. The S-phase precipitates are formed in the aging treatment of Al-Cu-Mg alloys. They were found to be more effective in increasing the hardness and strength of the alloy than the θ-phase ones[9-11].

Xu et al[12]. studied the effect of enhancing solution treatment and different artificial aging time to improve the strength of 2024 Al alloy, and observed the fracture surfaces. At 8 h artificial aging, the strength reached its peak at the state. Ebrahimi et al[13]. compared the hot deformation with strain rates of 0.001~0.1 s^{-1} at supersaturated and annealed temperatures. Kumaran[14] reported the ultrasonic parameters to evaluate the precipitation reaction in 2024 Al alloy. Pannaray et al[15]. presented the microstructure evolution during solution heat treatment of semisolid cast 2024 Al alloy. Radutoiu et al[16]. researched the influence of the artificial aging temperature on AA2024 microstructure. However, the previous researchers have not studied the quantitative analysis and evolution of AA2024 in natural aging strengthening. It is significant, therefore, to conduct quantitative analysis of the effect of natural aging time on the mechanical properties and microstructure of AA2024-O after solid solution. In order to investigate the effect of natural aging time on the strength of the AA2024, tensile mechanical behavior test was carried out. For this purpose, the heat-treated specimens were aged in different periods at room temperature.

1 Materials and Experimental Procedure

The material was heat-treated AA2024-O aluminum alloy, which was received in sheet form with nominal thickness of 1.5 mm. chemical composition of the AA2024 tested by QUANTA FEG 250 was Al-5.56Cu-1.36Mg-0.85Fe-0.59Mn (mass fraction, %), which is shown in Fig.1. The tensile specimens were made by wire cut electric discharge machine along the rolling direction. The dog-bone specimen dimensions were based on recommendations in ASTM:E8M-04, with a 60 mm parallel gauge length and a width of 12.5 mm in the reduced width section and an overall length of 200 mm. The dimensions are shown in Fig.2.

All of the specimens were solution heat treated at (495±5) ºC in a laboratory furnace for 35 min (heating for 25 min and keeping warm for 10 min) and then quickly quenched into cold water (20 ºC). For the sake of capturing the full range of AA2024 property evolution, aging times of 10 min, 1, 3, 12, 48, 60, 120, 360 h were investigated.

Each specimen was tested on a SUNS JXYA105C tensile testing machine at a rate of 30 mm/min. The longitudinal strains were measured by the test using a YYU-20/50 (50 gauge length) extensometer. Material Test software was applied to record the data throughout the test. For the purpose of obtaining accurate and reliable average data, three specimens were tested per different condition. The fracture surfaces were observed by SEM with QUANTA FEG 250 after the tensile test.

2 Results and Discussion

The key aim of the present paper is to study the evolution of mechanical properties of heat-treated AA2024-O at different natural aging time. Typical true stress-strain tensile flow curves could be seen in Fig.3. Aging times were selected in the range from 10 min to 360 h so as to correspond to all aging state, containing under-aging, peak-aging and

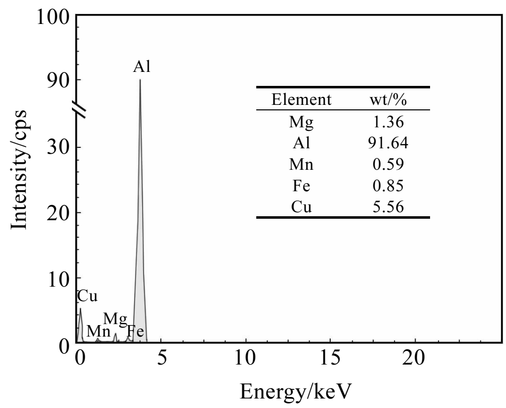

Fig.1 EDS analysis of the AA2024

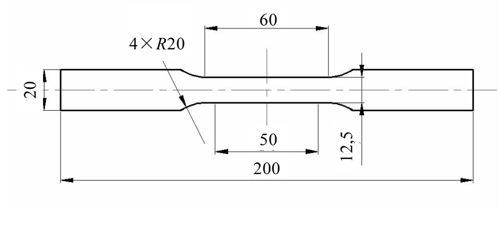

Fig.2 Dimensions of the specimen

over-aging. It is obvious that different natural aging conditions have a significant effect on the stress-strain flow curves. The values of yield strength and ultimate tensile strength are shown in Fig.4.

2.1 Mechanical test results

Conventional yield stress and ultimate tensile strength keep increasing up to a maximum of 60 h. For longer aging periods (>60 h), a gradual decrease in yield stress and ultimate tensile strength is noticed, while the ductility seems not to change much.

The critical true strain increases from 10 min to 3 h aging in a serrated manner. This phenomenon is a typical characteristic of the supersaturated solid solution, owing to the joint influence of the vacancy formed during quenching process and the interaction of (GP) zones[17]. During natural aging, the GP zones continue to grow and tend to trap vacancies, leading to increase the critical strain at which serrations occur. It is generally considered that 2xxx series aluminum alloy finished aging at room temperature within 96 h [7]. The consensus is recognized, 2xxx alloy is produced by flat rolling in actual industrial production, whose mechanical properties reached the standard before 96 h in the natural aging process. When the natural aging time is 120 and 360 h, the stress and strain curves tended to coincide. This furthermore proves that the AA2024 has been over aged and remained stable. Its yield stress and ultimate tensile strength are almost equal, but less than the values of the natural aging 60 h. Natural aging process has ended at 120 h. The natural aging process has ended at aging 120 h, among the selected natural aging time point.

2.2 Fracture surface analysis

The fracture surfaces were observed by scanning electron microscope (SEM) after tensile tests. Fig.5 presents SEM images for various natural aging times. The fractured surface shows a great many of dimples which is identified as a ductile fracture. As the natural aging time prolonged, the dimples become less and flat. The flatness of the dimples reveal moderate ductile fracture, which results in the increase of the yield stress and ultimate tensile strength of the AA2024. This corresponds with the stress-strain curves shown in Fig.3[2,9,18].

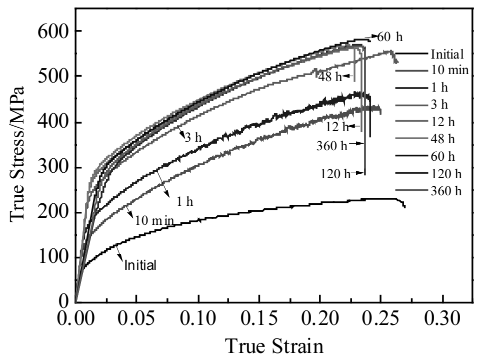

Fig.3 True stress-strain curves of the heat-treated AA2024

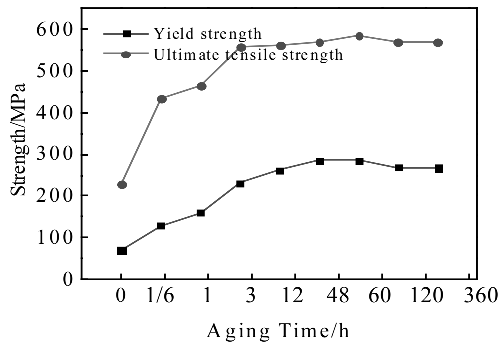

Fig.4 Values of yield stress and ultimate tensile strength of the heat-treated AA2024

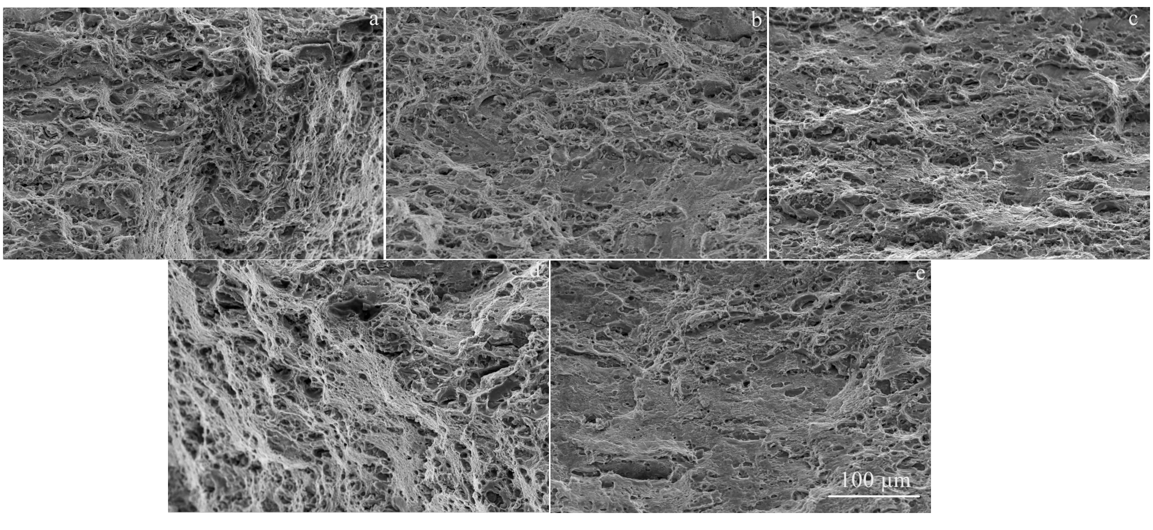

Fig.5 SEM fracture surface morphologies of AA2024 tensile specimen for different natural aging conditions: (a) initial, (b) 10 min, (c) 1 h, (d) 3 h, and (e) 12 h

2.3 Metallographic observation

Original microstructure and microstructure of AA2024 tensile specimen with solution aging after 60 h are shown in Fig.6 and Fig.7, respectively. After the aging of 60 h, the grain coarsening of the alloy can be clearly seen in Fig.7. The values of the tensile strength and the yield strength become larger, and the plasticity deteriorates in the macro aspect.

2.4 Natural aging strengthening prediction model

2.4.1 Model establishment

Leacock et al[19]. proposed a constitutive model based on the Voce hardening equation for the short-time natural aging of Al-Zn-Mg-Cu aluminum alloy, which was used to represent the constitutive relationship at a natural aging time:

$$\sigma = A + B(1 - e^{-m\varepsilon_p}) + C\varepsilon_p{}^n \quad (1)$$

where A is the uniaxial yield strength, B is the saturation stress parameter, ε_p is the plastic strain, m is the saturation stress work hardening parameter, C is the hardening coefficient , n is the second work hardening exponent and σ is the true stress.

In the Leacock's investigation, the B, m and n values at each aging time obtained by the fitting change little, while the C values vary greatly. However, the change of C value has little effect on strain strengthening. The hardening curves of each natural aging time in the test range were fitted, so that the coefficients of the equations at multiple aging time were obtained. After taking the average value, the coefficients of the model were obtained. Nevertheless, it is necessary to improve the calculation of yield strength in the model, to accurately predict the true stress-strain curves at each aging time.

Based on the observation of the effect of cold hardening on precipitation, the precipitation strengthening model under the action of pre-strain was proposed[20-22]. Leacock further proposed the equation to describe the stress change under aging[19]:

$$\Delta\sigma = \sqrt{\tfrac{3}{2}}k^{\frac{3}{2}}M\mu\frac{\sqrt{f_\upsilon R}}{b} \quad (2)$$

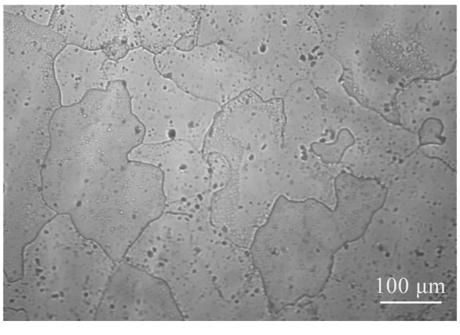

Fig.6 Original microstructure of AA2024 tensile specimen with solution aging after 60 h

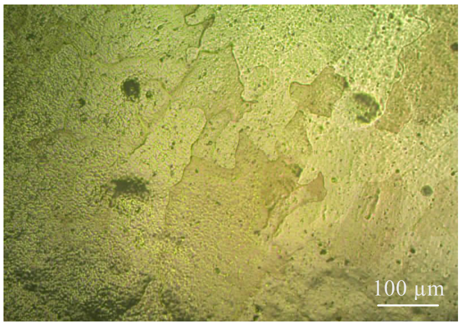

Fig.7 Microstructure of AA2024 tensile specimen with solution aging after 60 h

where $\Delta\sigma$ is the change in yield strength, k is determined by the size of the precipitate and its resistance to shear strength. M is the Taylor factor, μ is the shear modulus, b is the magnitude of Burgers vector, f_υ and R are the volume fraction and radius of the precipitate, respectively. Where R is a function of time[19]

$$R(t)=At^b \quad (3)$$

while A and b are constants and t is the time in seconds. For materials with different compositions, the relevant parameters in formula (2) are different, while the parameters such as f and R are relatively difficult to measure. Considering the above considerations, formula (2) can be rewritten as[19]:

$$\Delta\sigma(t)=Dt^g \quad (4)$$

where D and g are both material constants. The stress calculation model for different natural aging time can be expressed as

$$\sigma = A + B(1 - e^{-m\varepsilon_p}) + C\varepsilon_p{}^n + Dt^g \quad (5)$$

Using the above model, the modified constitutive model can be obtained, which is based on the 1.5 mm thickness sheet and the stress-strain curves at natural aging for 1, 3, 12, 48 and 60 h.

$$\sigma = 160.11 + 255.8[1 - \exp(-11.54\varepsilon_p)] + 633.1\varepsilon_p{}^{1.234} + 19.46\log(t) \quad (6)$$

2.4.2 Model verification

The fitted modified Voce model was used to calculate the real stress-plastic strain of 1.5 mm thick sheet metal at different natural aging time. The results are shown in Fig.8.

Comparing the test results with the stress-strain curves calculated by the modified Voce model，the results show that the established constitutive model can predict the true stress-plastic strain curve of materials at different aging time. The MSE and R values are 22.88 and 0.9662, respectively, and the correlation is shown in Fig.9. The standard error of the calculation results is small and has a strong

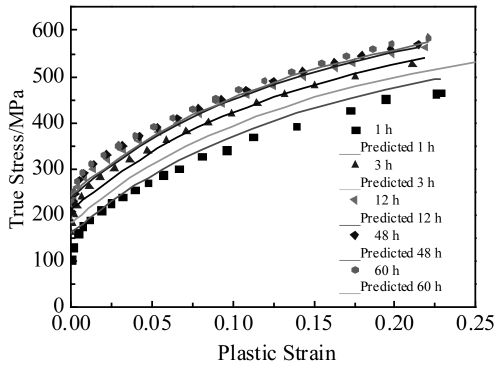

Fig.8 True stress-plastic strain curves of the modified model

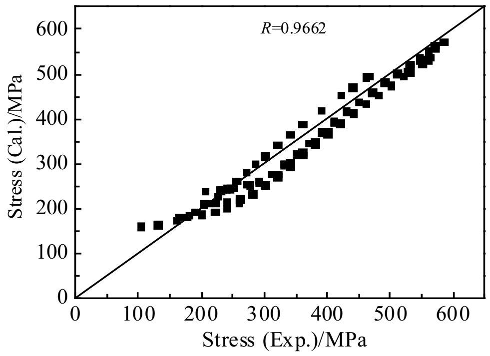

Fig.9 Correlation results between the stress prediction and the test

correlation with the experimental results. The modified Voce model is the most accurate stress prediction for natural aging time of 60 h.

3 Conclusions

1) Heat-treated AA2024-O was subjected to room temperature tensile test during aging treatment. The yield strength and tensile strength reach the highest when the aging time is 60 h. When aging for 120 h, the value of yield strength and tensile strength begin to decrease. When the aging time is 360 h, the values of the yield strength and tensile strength are basically as the same of 120 h. So the natural aging process has ended at aging for 120 h. The natural aging process has ended at aging for 120 h, among the selected natural aging time points.

2) During the initial stages of the aging treatment, GP zone formed from the heat-treated AA2024-O matrix. As a result, the yield strength and tensile strength values have improved remarkably.

3) After the specimens were stretched, their fractures were observed by the scanning electron microscope. The results show that it is a ductile fracture. During the aging treatment, the dimples gradually decrease and the plasticity gradually decreases.

4) An all-around mechanical test program has provided experimental data for modeling the naturally aged commercial 2024-O heat-treated sheet forming processes. And the constitutive equation is demonstrated to be capable of exactly representing the data set within experimental errors.

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热处理 2024-O 铝合金在自然时效下的拉伸性能及断口形貌演变

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摘　要：研究了时效时间对热处理后的2024-O铝合金试件的拉伸性能及断口的影响。采用室温拉伸法，研究了2024-O态铝合金经过热处理后不同时效时间试件的应力-应变曲线、屈服强度、抗拉强度，建立了能够预测应力的本构方程，并且通过观察断口，分析了时效时间对材料组织的影响。结果表明：随着时效时间的延长，试件逐渐强化，到某一时刻达到峰值，屈服强度、抗拉强度下降；采用SEM观察到断口处有大量韧窝，为韧性断裂，而且随着自然时效时间增长，试件断口的韧窝越来越少，塑性越来越差；建立了2024铝合金在自然时效下强化的本构方程，该模型能够较好地预测材料在自然时效下的应力。

关键词：2024铝合金；自然时效；时效强化；断口

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