Effect of pre-deformation and artificial aging on fatigue life of 2198 Al-Li alloy

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Abstract

The effects of pre-deformation and artificial aging on fatigue life of 2198 Al-Li alloy were explored to further reveal its fatigue behavior and improve the damage tolerance. Fatigue life was investigated on 2198-T3 alloy after pre-deformation and aging treatments. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to study the fracture morphology, precipitation behavior, fatigue crack initiation and propagation. Results indicated that T\(_1\) (Al\(_2\)CuLi) phase dominated the strengthening of 2198-T3 alloy after the further aging. Pre-deformation increased the number of dislocations in the matrix, which provided favorable position for nucleation of T\(_1\). The precipitation of \(\theta'\) (Al\(_2\)Cu) and \(\delta'\) (Al\(_3\)Li) were inhibited. Also, the formation and coarsening of precipitate-free zone (PFZ) were effectively avoided in this condition. Dislocation density in the 2198 Al-Li alloy matrix increased with the amount of pre-deformation, leading to an increase in micro-crack defects on the surface and inside alloy. As a result, decreased fatigue life and an increased crack growth rate of the alloy were observed. Overall, 2198 Al-Li alloy had the best fatigue life and damage tolerance enhancement after it underwent 3% pre-deformation and was aged at 155 °C for 15 h.

1. Introduction

The aluminum-lithium alloys have attractive applications in the aerospace industry owing to their lower density, better strength and higher stiffness comparing to the conventionally commercial 2xxx and 7xxx series aluminum alloys [1–8]. However, insufficient plasticity, toughness and obvious anisotropy prevent their universal uptake [9].

Alloys used in aviation fields [10–13] are always concerned with a desired damage tolerance, which requires not only high strength but also excellent plasticity, fracture toughness and fatigue. Aging treatments is one of the most important methods to improve plasticity and toughness of Al-Li alloys [14], which include single and multi-stage artificial aging and pre-deformation + artificial aging. Comparing with single or multi-stage aging, the combination of pre-deformation plus artificial aging increases the dislocation density and promotes non-uniform nucleation of the strengthening phase, which significantly improves the mechanical properties of the alloys [15–17]. However, investigations on the relationships among the pre-deformation, precipitation, and mechanical properties are limited. Especially for Al-Li alloys, only a few studies have comprehensively investigated the influence of pre-deformation before aging on the precipitation response as well as fatigue properties [18–20].

The new type 2198 Al-Li alloy belongs to the third generation Al-Li alloys used in large commercial aircraft. Commercial 2198 alloy used in large aircraft is always treated to T3 or T8 state. It is no doubt that 2198-T3 is more suitable for further forming or processing than 2198-T8 due to better plasticity. Forming and processing
conducted directly on 2198-T3 have the advantages of improving the production efficiency, reducing the number of shape corrections \([21–23]\). However, the processed 2198-T3 component requires a further aging to obtain higher strength. Reasonable aging treatment is particularly necessary so that the alloys could obtain high strength while still exhibit excellent toughness and fatigue performance. Hence, the effects of pre-deformation and artificial aging on tensile properties and fatigue life of 2198 Al-Li alloy were explored. The microstructure and precipitation behavior of alloys were investigated.

2. Experimental

2198-T3 Al-Li alloy sheet rolled to a thickness of 1.6 mm was used in this study. The composition of the alloy was shown in table 1.

Artificial aging treatments were conducted in a DHG-9623A constant temperature blast dryer with temperature uniformity less than \(±1\) °C. Previous research showed that the optimum strength and toughness of the 2198 Al-Li alloy were obtained under artificial aging at \(155\) °C for 15 h.

An INSTRON-8872 universal machine was used to conduct pre-tensile deformation. The 2198 Al-Li alloy was pre-deformed at 1%, 3%, and 5% along the rolling direction, as shown in figure 1.

The tensile test along the rolling direction was carried out on a CMT-5105 universal electronic testing machine. The strain values of the 2198 Al-Li alloy were measured using an extensimeter. According to standard ASTM E8/E 8M-13, a tensile rate of \(2 \text{ mm min}^{-1}\) was used. Each set of 5 specimens were tested to ensure the validity of the data.

The fatigue life test was conducted on a MTS 100 KN testing machine following the test standard ASTM E466. Central opening notch specimen \((K_t = 2.6)\) was adopted, as shown in figure 2. The center notch was processed via slow wire cutting to reduce the influence of residual stress. The surface of the specimen was polished with 1#, 3#, and 5# metallographic sandpaper before the fatigue life test, in order to minimize the effect of surface stress concentration. A stress ratio of \(R = 0.06\) and a loading frequency of \(f = 25\) Hz were chosen in the fatigue lift test.

The conditional fatigue limits of the 2198 Al-Li alloy after 3% and 5% pre-deformation were primarily measured using the up-and-down method. First, the specimens were tested at high stress level, and if it was failure before reaching the given limit cycle of \(1 \times 10^7\), the second piece then was tested at the lower stress level with stress increment of 3% ~ 5%. On the contrary, the test was carried out at the higher stress level.

The results were shown in figure 3. The fatigue limits were calculated using the lifting method, which could be written as formula 1:

![Figure 1. Diagram of pre-deformed specimen.](image)

Table 1. Chemical composition of 2198 Al-Li Alloy (mass fraction, %).

| Li  | Cu   | Mg      | Ag   | Zr   | Mn   | Zn   | Al   |
|-----|------|---------|------|------|------|------|------|
| 0.8 ~ 1.1 | 2.9 ~ 3.5 | 0.25 ~ 0.8 | 0.1 ~ 0.5 | 0.04 ~ 0.18 | ≤0.5 | ≤0.35 | Bal. |
where $m$ is the total number of valid tests (data points passed by the failure level are counted), $n$ is the test stress level series, $\sigma_i$ is the $i$-th stress level, and $V_i$ is the number of tests at $i$-th stress level.

Then, the fatigue life of the alloys was measured using the grouping test method. According to the loading conditions of the material in the actual engineering, the stress level was determined to be 254 MPa, 233 MPa, 212 MPa, 191 MPa, and 170 MPa. The tests were repeated three times at each stress level.

The crack initiation test was carried out on a MTS 50 KN testing machine with a stress ratio of $R = 0.1$ and frequency of $f = 15$ Hz. The fracture morphology was observed using a FEI Quanta 200 scanning electron microscope (SEM).

Phase precipitation behavior of the 2198 Al-Li alloy with different treatments was analyzed using an FEI-TECNAI G2 transmission electron microscope (TEM). Samples for TEM were prepared by electro-polishing in a twin-jet apparatus, using a 30% nitric acid-methanol solution at $-20 \degree$C under 15 V.

### 3. Results and discussion

#### 3.1. Tensile properties

Specimens of the 2198-T3 Al-Li alloy with 1%, 3%, and 5% pre-deformation were aged for various times at an aging temperature of 155 $\degree$C. The tensile properties are shown in figure 4.

The strength of the 2198 Al-Li alloy improves while the plasticity deteriorates with an increase in pre-deformation as well as aging time. Pre-deformation behavior significantly accelerates the aging response of 2198 alloy. The 2198 Al-Li alloy reaches the peak strength after 10 h with 5% pre-deformation, while requires more than 20 h to achieve the peaking aging state with 1% pre-deformation.

#### 3.2. Phase precipitation behavior analysis

Phase precipitation behavior was further investigated to better reveal the influences of pre-deformation and the artificial aging treatment on the fatigue of the 2198 Al-Li alloy. The precipitation morphologies of the alloy after different amounts of pre-deformation (1%, 3%, and 5%) are presented in figure 5.

$T_1$ ($Al_2CuLi$), $\theta'$ ($Al_3Cu$) and $\delta'$ ($Al_3Li$) were the main phases in 2198 Al-Li alloy after the pre-deformation of 1%. Only $T_1$, without $\theta'$, was observed in the alloy after the pre-deformation of 3% or 5%. Greater density of $T_1$...
phase precipitated in the matrix with an increasing pre-deformation. The size of the precipitated T1 phase differs obviously from 50 nm to 120 nm when the pre-deformation was 5%.

Cahn proposed a dimensionless parameter $\alpha$ to expresses the nucleation rate of the precipitate at dislocations \[ \alpha = \frac{\Delta G_v \mu b^2}{2\pi^2 \sigma^2} \] where $\Delta G_v$ is the change in volume-free energy, $\mu$ is the shear modulus, $b$ is the Burgers vector, $\sigma$ is the interfacial energy required to form a new surface, and $\alpha$ is a dimensionless parameter. The promoting effect of dislocations on nucleation of the strengthening phase increases with an increase in the $\alpha$ value. When $\Delta G_v$ and the magnitude of $b$ increases or $\sigma$ decreases, the probability of nucleation of the precipitated phase at dislocation increases.

Second phases are usually apt to precipitate when possess lowest formation energy barrier, which depends on the combined effects of volume-free energy, strain energy and interfacial energy. The stress field around the dislocation introduced by the pre-deformation causes the crystal to have high energy, which is equivalent to increase the free energy of the phase transition, thus reducing the formation energy barrier of T1 and $\theta'$. Therefore, T1 and $\theta'$ are easy to precipitate quickly at dislocation after introducing pre-deformation. However, the precipitation of T1 is in competition with $\theta'$. T1 is an equilibrium phase while $\theta'$ is a meta-stable phase, which indicated that T1 possesses higher $\Delta G_v$. Meanwhile, the shear strain of the $\theta'$ is at (001)\textsubscript{\alpha}/[100]\textsubscript{\alpha}, while the shear...
strain of the T1 is at (111)α/[112]α. Because the shear strain for T1 is in the plane of the Burgers vector of dislocation in the aluminum matrix, i.e., (111)α planes, dislocations may thus have a greater effect on T1 nucleation than that on θ' nucleation [28–31]. In addition, both T1 and θ' exhibit similar interfacial energy [32]. Hence, comparing with θ', dislocations have a greater effect on the nucleation of T1, which results in its preferentially precipitation. Meanwhile, the growth of T1 precipitates rapidly consumes the Cu atoms in the matrix, which inhibits the precipitation of θ'.

However, the strain energy as well as interfacial energy between θ' and the matrix are low, they tend to be dissolve in the matrix by homogeneous nucleation, so the precipitated morphology and quantity of the θ' are not affected by the pre-deformation [3, 33]. Meanwhile, the growth of T1 consumes Li atoms in the solid solution. The θ' dissolves and the volume fraction decreases. Therefore, the pre-deformation contributes the most to the precipitation of T1 and leads to their refinement. It is the reason that only T1 precipitates in the matrix after the pre-formation of 3% and 5%.

The T1 has a high stacking fault energy and has a non-coherent relationship with the matrix. The critical slitting stress of the cutting dislocation is much larger than the θ'. Dislocations pass through the T1 in a bypass manner instead of a cutting through manner. Therefore, the strength of the alloys after pre-deformation is improved. With an increase in the amount of pre-deformation, the dislocation density in the matrix increases. Great density of dislocation promotes the dispersion of T1, suppresses the coplanar slip of dislocations, and further increases the strength of the alloys.

Besides, the peaking aging treatment of 2198 alloy usually leads to the formation of precipitate-free zone (PFZ) [34, 35], which has been found adversely affected the fracture properties of the alloys by correlating mechanical properties to microstructure. 2198-T3 reaches the peak strength aging after 40 h at 155 °C. The PFZ with a width of 60–120 mm is observed at the grain boundary, as shown in figure 6(a). However, pre-deformation promotes the larger numbers of T1 precipitated with limited size, which hardly results in the formation and broadening of the PFZ, seeing figures 6(b) and (c). It is beneficial to the plasticity and toughness of the 2198 Al-Li alloy. The above results are similar to our previous research on the 2060 alloy [36].

The fatigue limits of the 2198 Al-Li alloy decreases with an increase in pre-deformation under the same aging temperature and time, and this is mainly related to the size, morphology, and distribution of the aging precipitation phase. In the pre-deformation treatment, the slip dislocation is entangled around the coarse brittle phase, causing the cracks to nucleate. The cracks further extend into the interior of the matrix, and this increases micro-crack defects in the sample [37]. The generation of micro-cracks leads to the premature initiation of fatigue cracks, and this reduces the fatigue life of the alloys. Pre-deformation before aging increases the density of defects in the matrix. A large number of T1 are dispersed in the sample. When the shear stress of the dislocation cutting through the T1 increases, it is more difficult to form a coplanar slip. It is difficult to alleviate the cumulative damage at the crack tip when the driving force required for crack propagation increases. Therefore, the rate of fatigue crack growth increases.

3.3. Fatigue lifetime and S-N curves

The S-N curves of the 2198 Al-Li alloy with different amounts of pre-deformation are shown in figure 7. There is no apparent difference in fatigue life of the 2198 Al-Li alloy after 3% and 5% pre-deformation at high stress levels. A decrease in the stress level highly increases the fatigue life of the alloy when the amount of pre-deformation is small. A high fatigue fracture life could be achieved under a low stress level, and the fatigue damage resistance of the small pre-deformed alloy is better than that of the large pre-deformed alloy. For example, when $\sigma_{\text{max}} = 149$ MPa, the fatigue life ($N_f$) of the notched specimen of the 5% pre-deformed alloy is between $10^6$ and $10^7$, whereas the fatigue life ($N_f$) of the notched specimen of the 5% pre-deformed alloy is $2.86 \times 10^5$. The damage resistance is significantly different for the alloy with different amounts of pre-deformation. Along with the study of phase precipitation behavior, with an increase in the amount of pre-deformation, an increase in the dislocation density of the matrix leads to production of internal micro-crack of the alloy, and this results in a decrease in the fatigue life of the alloy. Therefore, when the amount of pre-deformation is larger, the fatigue life of the 2198 Al-Li alloy is shorter, and the ability to resist fatigue accumulation damage is weaker.

3.4. Fracture analysis

Fatigue fracture morphologies of the 2198 Al-Li alloy after pre-deformation and aging strengthening are shown in figure 8. The fracture shown in figure 8(a) is mainly divided into three regions: crack initiation (or source) zone (I), crack growth zone (II), and final rapid fracture area (III). multiple fatigue crack sources originate on the surface of the sample, owing to the obvious stress concentration and rough surface around the notch of the sample The early extension zone of the fatigue crack is shown in figure 8(b). The crack propagates along the primary slip plane under the alternating load. The section shows obvious crystallographic characteristics,
following with the river patterns and sliding steps. Then, the crack propagates into the stable-state, as seen in figures 8(c)–(e). In the stable crack growth zone, the crack propagates in a direction perpendicular to the normal stress. It leads to the formation a series of mutually parallel and slightly curved wavy stripes, which is the typical
fatigue striation. The spacing between fatigue striations increases significantly when the crack propagated into the interior of the alloy. The interspace is 645 mm when the crack length is 3 mm while it increases to 940 nm when the crack length increases to 4 mm. The striations spacing increases to 1.4 μm when the crack length is 10 mm. In addition, the fatigue section in the stable crack growth zone is composed of many small fault blocks with different heights and sizes. The discontinuous and nonparallel fatigue striations on the small fault blocks propagate in the same direction. In the final stage of crack propagation, the remaining section of the sample is not strong enough to withstand the external applied stress, which leads to instability and rapid fracture of the sample, seeing figure 8(f). The fracture of the alloy appears parallel cleavage plane located at different heights. In addition, there are dense dimples on the fracture surface, and some small second phase particles are distributed at the bottom of the dimples. The mixture of cleavage fracture and inter-granular fracture is obtained.

Samples of the 2198 Al-Li alloy with 3% and 5% pre-deformation fracture respectively after 23 465 and 18 816 cycles under the stress level of $\sigma_{\text{max}} = 254 \text{ MPa}$. The fatigue fracture morphologies are shown in figure 9. In both of the samples, fracture generates from the edge of the notch and the propagates to the center. In the steady-state growth expansion region, the 5% pre-deformed alloy has a fatigue striations interspace of 1.04 μm, which is significantly larger than that the 834 nm in 3% pre-deformed alloy as shown in figures 9(c) and (d). The above results indicate that the increasing pre-deformed aggravates the fatigue crack growth in the alloy, leading to a reduction in fatigue life.
3.5. Fatigue crack initiation and early propagation path

SEM image of crack initiation and the early propagation path is shown in figure 10. The crack initiates at the edge of the sample and then propagates approximately perpendicular to the loading direction. Usually, fatigue crack easily initiates around impurity particles (e.g., AlCuLiMg and AlFeMnSi), the interface between impurity and the matrix, or the stress concentration area like grain boundaries, sub-grain boundaries [38, 39]. According to our experiment, impurities are not observed at the crack initiation site, which indicates that high stress concentration on the edge of the sample was the main cause for the generation of micro-crack. The crack is initiated in the region where there is serious local plastic deformation. Cracks are constantly deflected during the expansion process and bifurcation occurred. Grain boundaries strongly inhibit crack propagation and cause bifurcation and secondary cracks. Magnified images of the cracks at the three points marked as b, c, and d in figure 10(a) are shown in figures 10(b)–(d). As a result of severe plastic deformation in the peripheral region of the crack during the expansion process, the crack propagation path is meandered, and the crack surface is convex or concave with respect to the surface of the substrate (figure 10(b)). The crack bifurcates, and many tiny cracks are generated around the crack, as observed in figures 10(b) and (c). There are no second phase particles or impurities observed around the crack. Probably because of the weak boundary or sub-grain boundary, the stress concentrates at the crack tip and eventually leads to cracks to form along grain boundaries. The crack has a large angle deflection, and a distinct crack branch appears at a 45° angle to the main crack (figure 10(d)).

A large number of vacancies, dislocations and other defects exist on the grain boundary of 2198 Al-Li alloy, submitting to higher stress concentration. Meanwhile, the existence equilibrium phase makes the weaker resistance to stress concentration and micro-crack initiation relative to the matrix. Under the strong stress field at the tip of the micro-crack, dislocations are easy to form pile-up at the grain boundary, which makes the stress concentration intense and produces a large number of persistent slip bands (PSBs) [40]. Cycle slips in the sample surface form into grooves and extrusion ridges (figures 10 and 11), which lead to the stress concentration in the rough area. The PSB rough area is easy to break away from the matrix material and form fatigue cracks in the rough surface under the action of the applied stress.

Furthermore, the PSB starts at about 45° along the loading direction (figure 10). Then, the crack propagation direction is gradually perpendicular to the loading direction, since the large angle grain boundary strongly hinder the movement of the PSB.
When the crack propagates to the maximum tensile stress surface, the crack propagation expands into the second stage, forming a large number of fatigue lines. The fatigue-cracking ‘plastic passivation model’ proposed by Larid explains the formation mechanism [41]. The crack tip expands with an increase in cyclic stress at the

**Figure 10.** SEM images of the early propagation path of the crack initiation stage in the 2198 Al-Li alloy: (a) the early propagation path of the crack initiation stage in the 2198 Al-Li alloy and (b)–(d) enlarged image of cracks at (b)–(d).

**Figure 11.** Schematic diagram of dislocation slip forms an intrusion trench and an extruded ridge.
beginning of the cycle, and the crack slips along the direction of the maximum shear stress because of high stress concentration. The crack tip is passivated and is semicircular when stress increases. When the stress is unloaded, the open crack tip sharpens and closes in the residual dislocation slip zone. However, the newly formed crack surface does not disappear, and the crack becomes sharp again under the maximum cyclic compressive stress. An increase of $\Delta a$ [41] is observed in the newly formed crack. In the subsequent cyclic loading process, the crack undergoes passivation, expansion, and sharpening one more time, this leaves marks during the sharpening process, and these marks are called fatigue fringing.

4. Conclusions

(1) The 2198-T3 Al-Li alloy had a significant strengthening effect after pre-deformation and artificial aging. Pre-deformation significantly accelerated the aging response of 2198 alloy. Meanwhile, Pre-deformation increased the dislocation density of the matrix, which was beneficial for the dispersive precipitation of the $T_1$ phase. Also, the well-dispersed $T_1$ hardly resulted in the formation and broadening of the PFZ. Hence, the strength of the 2198 Al-Li alloy after artificial aging was significantly improved. Furthermore, pre-deformation alleviated the deterioration of plasticity and toughness, following with the increasing strength during the aging.

(2) The fatigue life of the 2198-T3 Al-Li alloy decreased with an increase in the pre-deformation amount. The fatigue limit of the Al-Li alloy was 150 MPa when the pre-deformation amount was 3%, whereas the fatigue limit was only 107.8 MPa when the pre-deformation amount was increased to 5%. The fatigue fracture was composed of three parts, which include the crack initiation (or source) zone, the crack growth zone and the final fracture area. Obvious fatigue striations were observed in the crack growth zone.

(3) The fatigue crack of 2198 Al-Li alloy plate was initiated at the stress concentration on the surface, and continuously deflected under the action of grain boundary. The crack propagated perpendicular to the stress loading direction. An increase in the pre-deformation of the alloy accelerated fatigue crack growth, reduced fatigue life of the alloy, and increased the fatigue crack growth rate. The 2198 Al-Li alloy had the best strength, plastic toughness, and fatigue performance after 3% pre-deformation and aged at 155 °C. Also, the damage tolerance ability was enhanced.

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References

[1] El-Aty A A, Xu Y, Guo X Z, Zhang S H, Ma Y and Chen D Y 2018 Strengthening mechanisms, deformation behavior, and anisotropic mechanical properties of Al-Li alloys: a review J. Adv. Res. 10 49–67
[2] El-Aty A A, Xu Y, Zhang S H, Ha S Y, Ma Y and Chen D Y 2019 Impact of high strain rate deformation on the mechanical behavior, fracture mechanisms and anisotropic response of 2060 Al-Cu-Li alloy J. Adv. Res. 18 19–37
[3] Li J F, Ye Z H, Liu D Y, Chen Y L, Zhang X H, Xu X Z and Zheng Z Q 2017 Influence of pre-deformation on aging precipitation behavior of three Al-Cu-Li alloys Acta Metall. Sin. (Engl. Lett.) 30 133–45
[4] Ma J, Yan D S, Rong L J and Li Y Y 2015 Effect of aging on the microstructure and mechanical properties of 1460 alloy Acta Metall. Sin. (Engl. Lett.) 28 454–9
[5] Bois-Brochu A, Blais C, Goma F A T, Larouche D, Boselli J and Brochu M 2011 Al-Li alloy 2099-T83 extrusions: static mechanical properties, microstructure and texture Adv. Mater. Res. 409 29–34
[6] El-Aty A A, Xu Y, Ha S Y and Zhang S H 2018 Computational homogenization of tensile deformation behaviors of a third generation Al-Li alloy 2060-T8 using crystal plasticity finite element method Mater. Sci. Eng. A 731 583–94
[7] Zhang X S, Chen Y J and Hu J L 2018 Recent advances in the development of aerospace materials Prog. Aerosp. Sci. 97 22–34
[8] El-Aty A A, Zhang S H, Xu Y and Ha S Y 2019 Deformation behavior and anisotropic response of 2060 Al-Cu-Li alloy: experimental investigation and computational homogenization-based crystal plasticity modeling J. Mater. Res. Technol. 8 1235–49
[9] Examilioti I N, Kluesmann B, Kashaev N, Riekers S, Enz J and Alexopoulos N D 2017 Anisotropy and size effect in tensile mechanical properties of Al-Cu Li 2198 alloy Proced. Struct. Integr. 5 13–8
[10] Rui J, He X F and Li Y H 2018 Individual aircraft life monitoring: an engineering approach for fatigue damage evaluation Chinese J. of Aeronaut. 31 727–39
[11] Talreja R and Phan N 2019 Assessment of damage tolerance approaches for composite aircraft with focus on barely visible impact damage Compos. Struct. 219 1–7
[12] Ashforth C and Illeczewicz I 2018 Certification and compliance considerations for aircraft products with composite materials Compr. Compos. Mater. 11 31–25
[13] Ansel H and Blom F F 2001 Fatigue: damage tolerance design Encyclopedia of Materials: Science and Technology (2nd edn.) (New York: Elsevier) pp 2906–10
[14] Wu L, Zhou C, Li X F, Ma N H and Wang H W 2018 Effects of TiB2 particles on artificial aging response of high-Li-content TiB2/Al-Li composite J. Alloys Compd. 749 189–96
[15] Lu Y L, Wang J, Li X C, Chen Y, Zhou D S, Zhou G and Xu W T 2017 Effect of pre-deformation on the microstructures and properties of 2219 aluminum alloy during aging treatment J. Alloys Compd. 699 1140–5
[16] Kang Y H, Wang X X, Zhang Y, Yan H and Chen R S 2017 Effect of pre-deformation on microstructure and mechanical properties of WE43 magnesium alloy Mater. Sci. Eng. A 689 435–45
[17] Wang H M, Yi Y P and Huang S Q 2016 Influence of pre-deformation and subsequent ageing on the hardening behavior and microstructure of 2219 aluminum alloy forgings J. Alloys Compd. 685 914–8
[18] Gholami M, Altenberger I, Vesely J, Kuhn H A, Wollmann M, Janecek M and Wagner L 2016 Effects of severe plastic deformation on transformation kinetics of precipitates in CuNi3Si1Mg Mater. Sci. Eng. A 676 156–64
[19] Ma P P, Zhan I H, Liu C H, Wang Q, Li H L, Liu D B and Hu Z G 2019 Pre-strain-dependent natural ageing and its effect on subsequent artificial ageing of an Al-Cu-Li alloy J. Alloys Compd. 798 8–18
[20] Li H Y, Kang W and Lu X C 2015 Effect of age-forming on microstructure, mechanical and corrosion properties of a novel Al-Li alloy J. Alloys Compd. 640 210–8
[21] Li H G, Ling J, Xu Y W, Sun Z G, Liu H B, Zheng X W and Tao J 2015 Effect of aging treatment on precipitation behavior and mechanical properties of a novel aluminum–lithium alloy Acta Metall. Sin. (Eng. Lett.) 28 671–7
[22] Liu L L, Pan Q L, Wang X D and Xiong S W 2018 The effects of aging treatments on mechanical property and corrosion behavior of spray formed 7055 aluminum alloy J. Alloys Compd. 735 261–76
[23] Liu F, Liu Z Y, Liu M, Hu Y G, Chen Y and Bai S 2018 Analysis of empirical relation between microstructure, texture evolution and artificial ageing of an Al-Cu-Li alloy during different pre-aging processes Mater. Sci. Eng. A 726 309–19
[24] Cahn J W 1957 Nucleation on dislocations Germination sur les dislocations Keimbildung an versetzungen Acta Metall. 5 169–72
[25] Cassada W A, Shillett G J and Starke E A 1991 The effect of plastic deformation on Al2CuLi(T1) precipitation Metall. Trans. A 22 299–306
[26] Ma P P, Liu C H, Ma Z Y, Zhan I H and Huang M H 2019 Formation of a new intermediate phase and its evolution toward $\theta'$ during aging of pre-deformed Al-Cu alloys J. Mater. Sci. Technol. 35 885–90
[27] Liu C H, Ma Z Y, Ma P P, Zhan I H and Huang M H 2018 Multiple precipitation reactions and formation of $\theta'$-phase in a pre-deformed Al-Cu alloy Mater. Sci. Eng. A 733 26–38
[28] Jiang B, Cao F H, Wang H S, Yi D Q, Jiang Y, Shen F H, Wang B and Liu H Q 2019 Effect of ageing time on the microstructure evolution and mechanical property in an Al-Cu-Li alloy sheet Mater. Sci. Eng. A 740–741 157–64
[29] Wang X M, Li G A, Jiang J T, Shao W Z and Zhen L 2019 Influence of Mg content on ageing precipitation behavior of Al-Cu-Li-x alloys Mater. Sci. Eng. A 742 138–49
[30] Yuan Z S, Lu Z, Xie Y H, Dai S L and Liu C S 2007 Effect of plastic deformation on microstructure and properties of high strength Al-Cu-Li-x Aluminum-Lithium alloy Rare Metal Mat Eng 36 493–6
[31] Huang B P, Zheng Z Q, Yin D F and Mo Z M 1996 Effect of trace Ag and Mg additions on mechanical properties and microstructures of 2195 alloy Mater. Sci. Forum 217–222 1239–44
[32] Li D Y and Chen L Q 1998 Computer simulation of stress-oriented nucleation and growth of $\theta'$ precipitates in Al-Cu alloys Acta Mater. 46 2573–85
[33] Gable B M, Zhu A W, Coontos A A and Starker E A 2001 The role of plastic deformation on the competitive microstructural evolution and mechanical properties of a novel Al-Li-Cu-X alloy J. Light Met. 1 11–14
[34] Dwyer C, Weyland M, Chang L Y and Muddle B C 2011 Combined electron beam imaging and ab initio modeling of $\theta_1$ precipitates in Al-Li-Cu alloys Appl. Phys. Lett. 98 201909
[35] Lin Y, Zheng Z Q, Li S C, Kong X and Han Y 2013 Microstructures and properties of 2099 Al-Li alloy Mater. Charact. 84 88–99
[36] Li H G, Hu Y B, Ling J, Sun Z G, Liu H B, Zheng X W and Tao J 2016 Effect of pre-aging on microstructure and properties of a novel aluminum-lithium alloy Rare Metal Mat Eng 45 465–59
[37] Hu L B, Zhan I H, Liu Z L, Shen R L, Yang Y L, Ma Z Y, Liu M, Liu J, Yang Y G and Wang X 2017 The effects of pre-aging on the creep aging behavior and mechanical properties of Al-Li-Si alloys Mater. Sci. Eng. A 703 496–502
[38] Li H Y, Huang D S, Kang W, Liu J, Ou Y X and Li D W 2016 Effect of different aging processes on the microstructure and mechanical properties of a novel Al-Cu-Li-alloy J. Mater. Sci. Technol. 32 1049–53
[39] He C, Wu Y J, Peng L M, Su N, Chen Q, Yuan S C, Liu Y and Wang Q Y 2019 Effect of microstructure on small fatigue crack initiation and early propagation behavior in Mg-10Gd-Y-0.3Zr alloy Int. J. Fatigue 119 311–9
[40] Zhong J, Zhong S, Zheng Z Q, Zhang H F and Luo X F 2014 Fatigue crack initiation and early propagation behavior of 2A97 Al-Li alloy Trans. Nonferrous Met. Soc. China 24 503–9
[41] Laird C 1979 Mechanisms and theories of fatigue Fatigue Microstruct (Metals Park OH: ASM: Springer) pp 149–203