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Role of thermal-mechanical loading sequence on creep aging behaviors of 5A90 Al-Li alloy

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A R T I C L E I N F O

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A B S T R A C T

Creep age forming (CAF), under thermal-mechanical environment, may be sensitive to the thermal and mechanical loading conditions. Unfortunately, the different creep aging (CA) behaviors under two inverse thermal-mechanical loading sequences, viz. loading-heating (LH) and heating-loading (HL), are almost neglected in experiments or modeling of CAF. In this work, taking solution treated 5A90 Al-Li alloy as a case material, the loading sequence related CA behaviors of the alloy are investigated using continuous/interrupted tensile CA tests at 130 °C/175 MPa combined with high-resolution Transmission Electron Microscope (HRTEM) and mechanical properties tests. The results show that, the inverse loading sequences result in different initial tempers for CA process, viz. solution temper under LH and stress-free aged temper under HL. The solution temper for CA process under LH can lead to a more stable and repeatable CA process than HL does, which causes a stress-free aged temper with randomly and discretely distributed precipitates for CA process. After two inverse loadings and 18 h of isothermal CA, the total creep deformation for LH (0.1475%) is twice larger than that for HL (0.0720%), thanks to the remarkable creep strain in the LH non-isothermal CA process with 49.2% of total creep strain. The samples under LH present a lower strength and a higher elongation than those under HL during the whole process, and the gap of the mechanical properties of samples under the two loading sequences reaches its maximum (15 MPa for yield strength and 8.45% for elongation) after 0.5 h of isothermal CA, and then gradually decreases in subsequent process. After 0.5 h of isothermal CA, though the volume fraction of the δ′ precipitates (Al_3Li) under LH is larger than that under HL, the dislocations density under LH is less than that under HL, which makes a lower material strength under LH. It is noted that, after 18 h of isothermal CA, the microstructures and macroscopic mechanical properties of the samples have less disparity for the two inverse loading sequences.

1. Introduction

The large integral panel, which has been widely used in aerospace because of its high reliability, high structural efficiency and light weight, has a feature of large volume, complex structure, uneven thickness and various curvatures, bringing great challenge for its forming manufacturing. Compared with the traditional forming technologies such as peen forming, stretch forming and bending forming, creep age forming (CAF) technology, which has small residual stress and good repeatability, is more suitable for forming the large integral panel. CAF concurrently shapes and heat-treats the workpiece under an elastic loading at an elevated temperature (Zhan et al., 2011a). Apart from creep deformation during CAF process, aging hardening also plays an important role, thus achieving the target shapes and properties simultaneously (Tekkaya et al., 2015). Furthermore, CAF is a complex physical process containing loading, heating and holding stages, and the deformation of the workpiece is much sensitive to the thermal-mechanical loading sequences, viz., loading-heating (LH) and heating-loading (HL). The creep and aging behaviors under different loading sequences are urgently to be explored to ensure the precision forming of both shapes and properties of the panels.

In aerospace industry, meanwhile, light-weight and high-performance metallic materials are still the best selection for structural components. Al-Li alloy, known for its advantages of low density, high elastic modulus, high specific strength and high specific stiffness, is considered to be the most ideal light weight and high strength structural material in aerospace field (Rioja, 1998). 5A90 Al-Li alloy (an Al-Mg-Li alloy), based on 1420 Al-Li alloy invented by the former Soviet Union, has a good overall performance and great potential for aerospace applications. With an initial solution temper, the alloy can be significantly strengthened by further artificial ageing, making it a promising candidate for the CAF process. To explore the forming

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potential of the alloy, it is necessary to find out the role of loading sequence on the creep deformation as well as the microstructure and properties of 5A90 Al-Li alloy.

In recent years, Al-Mg-Li alloy has been studied by a large number of scholars. Murken et al. (2003) studied the microstructural evolution during combined thermal and mechanical loading of an Al-Mg-Li alloy and pointed out that the strain path to reach a fixed strain plays an important role in the microstructural evolution. Deschamps et al. (2012) systematically investigated the precipitation behavior in an Al-Mg-Li alloy (1420) for both isothermal and non-isothermal heat treatments, finding that the δ′ phase is shown to form with Mg content similar to that of the alloy in the investigated temperature range. Li et al. (2010) analyzed the strengthening mechanism of an Al-Mg-Li alloy during retrogression and reaging treatment by SAXS method, including the δ′ precipitation behavior. In addition to the research on the microstructure of Al-Mg-Li alloy mentioned above, its formability and forming methods have also been extensively studied. Song et al. (2014) presented that pulse current can significantly improve the elongation and reduce the flow stress of 5A90 Al-Li alloys. Sidhar et al. (2016) evaluated the weldability of Al-Mg-Li alloy (1424) by the method of friction stir welding (FSW) and revealed the effect of thermal history on final weld properties. Ye et al. (2009) developed a novel thermo-mechanical process for producing fine-grained Al-Mg-Li alloy 1420 sheet for superplasticity and the layers of different microstructures along the normal direction of the sheet were observed. To sum up, however, little attention has been paid to the study of CA behavior of Al-Mg-Li alloy, neither the macroscopic creep deformation nor the microstructure evolution.

Many experimental and numerical researches on CA behaviors have been carried out during the past decades. For uniaxial CA experiment, Zhan et al. (2014) conducted series of tests to investigate the effects of process parameters on mechanical properties and microstructures of 2124 aluminum alloy in CA process, presenting that creep strain and creep rate increase with increasing aging time, temperature and applied stress. Lei et al. (2017) selected three initial temper – solution, retrogression and re-solution – to demonstrate the effect of different initial tempers on the microstructure and properties of creep aged 7050 aluminum alloy, and the re-solution temper was concluded to be the be a preferable selection to obtain high performance of the components. Li et al. (2016) studied the creep aging behaviors of Al-Cu-Li alloy under uniaxial tension and compression stress, respectively, finding that the creep strain under tensile stress is greater than that under compressive stress. Similarly, the asymmetric tensile and compressive creep behavior was observed by Zhang et al. (2015). It is noted that the above uniaxial CA experiments are all carried out at the condition of heating before loading, with the other loading sequence being rarely involved. For experiments on creep age forming of aluminum alloy sheet, Jeshvaghani et al. (2011) implemented experimental investigations of springback of 7075 aluminum alloy in creep age forming process, indicating that springback increases with decreasing time and temperature. Yang et al. (2016) introduced pre-deformation to AA2219 plate before CAF progress, leading to a remarkably reduced springback. Zhang et al. (2016) investigated the influence of deformation degree on the creep age forming of 7475 aluminum alloy and proposed a suitable deformation range. The loading sequence of traditional CAF experiments of aluminum alloy panels is loading before heating, where the stress are almost completely relaxed in the heating stage. However, the effect of the heating process is neglected by most scholars, with only the process after heating being investigated. Moreover, the constitutive equations, which are mostly based on uniaxial CA tests under the condition of heating before loading, are mistaken by many investigators to simulate the CAF process of panels under the condition of loading before heating (Zhan et al., 2011b).

In this work, taking 5A90 Al-Li alloy as the test material, a series of continuous/ interrupted uniaxial CA test under two different loading sequences – loading before heating (LH) and heating before loading (HL) – are carried out. Combined with high-resolution Transmission Electron Microscope (HRTEM) and mechanical properties tests, the effect of loading sequences on creep deformation, mechanical properties and microstructures, in terms of rules and mechanisms, are comparatively analyzed and discussed. This work could contribute to find a promising loading sequence in CAF process to ensure forming precision.

Table 1
Chemical composition of 5A90 Al-Li alloy (wt.%).

Mg	Li	Ti	Zr	Cu	Si	Fe	Al
5.6	2.3	< 0.002	0.10	0.002	< 0.0005	0.04	Bal.

2. Experimental procedures

2.1. As-received material and heat treatment

A commercial light weight 5A90 Al-Li alloy was used in this study with the chemical compositions listed in Table 1. The as-received material (T3S) is a 2 mm thick hot rolled plate provided by Southwestern Aluminum (group) Co., Ltd, China. According to GB/T 2039 – 1997, the test samples with the gauge length of 50 mm were machined along the rolling direction of the plate by the wire-electrode cutting, and the geometry and the size of the specimens are shown in Fig. 1. Then samples were solution treated in the electrical resistance furnace for 30 min at 460 °C, followed by water quenching at ambient temperature. TEM bright field image shows that there is hardly any precipitate but few dislocations in solution treated 5A90 Al-Li alloy, as shown in Fig. 2. Subsequently, the samples were subjected to CA tests within 30 min so as to avoid natural aging.

2.2. Artificial aging tests for determining experimental procedures

In order to determine the appropriate CA time and temperature, interrupted artificial aging (AA) tests were carried out. Samples for AA tests were machined out from the 2 mm thick plate, with a square size of 10 × 10 mm. After solution treatment, the samples were immediately put into the drying oven which was preheated to a certain temperature. Once time was up, the sample was taken out and cooled in cold water. The temperatures selected for AA tests were 100 °C, 130 °C and 160 °C, and the duration was defined according to the imminent peak aging time. Hardness test was conducted after AA tests, as shown in Fig. 3.

The hardness curves of artificial aged 5A90 Al-Li alloy under three temperatures of 100 °C, 130 °C and 160 °C are shown in Fig. 4. Obvious age strengthening phenomenon can be seen from the hardness evolution under the three selected temperatures. For AA behavior under 100 °C, the hardness continuously increases with time, with no downward trend appearing, meaning that peak aging has not yet come. While for that of 130 °C and 160 °C, there appears a sharp rise firstly, following a slowing increase rate and a final decline. By contrast, the over aging under 160 °C appears earlier with a sharper decline of hardness than that under 130 °C. Considering the practical duration of CAF process and the material properties, the temperature and duration for CA tests are determined as 130 °C and 18 h.

2.3. Design of continuous/interrupted tensile creep aging tests

The constant-stress CA tests were implemented on a specified 100 kN electronic creep aging testing machine with an assisting furnace. According to the results of hardness test of artificial aged samples, the temperature and maximum duration for CA process were determined as 130 °C and 18 h (excluding the heating stage), respectively. And three elastic stresses of 125 MPa, 150 MPa and 175 MPa were chosen, slightly lower than the yield strength of solution treated 5A90