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Deformation behavior of Al-Cu-Mg alloy during non-isothermal creep age forming process

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ABSTRACT

Creep age forming process (CAF) has been developed for manufacture large aircraft components. Generally, in CAF, the component should experience heating, soaking and cooling stages. In order to acquire high precision of the creep-age formed components, the non-isothermal deformation behavior of Al-Cu-Mg alloy was investigated using the creep ageing, thermal expansion, hot tensile and creep age forming tests. During non-isothermal creep ageing process, both the elastic and thermal deformations grow in the heating stage. However, the elastic deformation drops to a certain degree and then the contraction occurs in the cooling stage. The non-isothermal creep deformation can be divided into six stages, in which the creep rate increases in the heating stage and decreases in the soaking and cooling stages. Under different applied stresses, the creep strain in the heating stage of the non-isothermal creep is about 22.28–26.86% of the total creep strain. Compared with the isothermal creep ageing process, steady-state creep rate of the non-isothermal creep ageing process is reduced. Nevertheless, total creep deformation in the non-isothermal creep ageing process is improved. Thus, the springback of the non-isothermal creep-age formed plate is smaller than that of the isothermal creep-age formed plate. It can be concluded that the creep behavior in non-isothermal conditions, particularly the heating stage, needs to be considered in CAF applications.

1. Introduction

Al-Cu-Mg (2000 series) alloys, of low density and high damage tolerance, are widely used in large aircraft components as delineated by Dursun and Soutis (2014). These large aircraft components are generally manufactured by creep age forming (CAF) process that simultaneously strengthens the part and changes its shape in a one-step forming and heat treatment process. Zhan et al. (2011) described that CAF takes the advantage of heat treatment cycle to release stresses under the effect of temperature and time through creep mechanism. Yang et al. (2017) stated that this technology is suitable for fabricating large-contoured aircraft wing skins. Successful applications of CAF reported by Ho et al. (2004a,b) include the upper wing skins of the Gulfstream GIV, B-1B combat aircraft and Airbus A330/340/380. However, the component should experience heating, soaking and cooling stages during the process of CAF. Especially for the forming process of large-scale components, they need long heating and cooling time. Thus, it is necessary to study the non-isothermal creep behaviors of Al-Cu-Mg alloy for their CAF applications.

In the past, researchers have paid attention to the creep behavior at different temperatures. Sherby et al. (1957) studied the activation energy for creep of high-purity aluminum and found below 0.25Tm the activation energy for creep was found to decrease rapidly with decreasing temperature. Dorn and Dill (1961) consider that the creep process control by atomic diffusion mechanism and the relationship between steady-state creep rate and temperature was established by using the Arrhenius equation. Then, Li et al. (1997) investigate the creep behavior of 2124 aluminum alloy and found that the apparent activation energy for creep is much higher than that for self-diffusion in aluminum. Meanwhile, a threshold stress, σ_{th}, whose temperature dependence is much stronger than that attributable to the shear modulus was revealed by analysis of the creep data. For the creep age forming process in Al-Cu-Mg alloy, Zhan et al. (2012) investigated the combined effects of ageing temperature, time and part thickness on springback, mechanical properties and microstructures of creep age forming of 2524 aluminum alloy sheets. They found that the springback is the most

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sensitive factor in the creep ageing parameters. Zhang et al. (2013) studied the creep age forming of AA2124 with single/double curvature and showed that the springback rate would be the minimum under the optimal coupling conditions among the temperature, ageing time and internal stress state of material. Zhan et al. (2013) studied the springback for 2124 aluminum alloy during creep ageing forming and compared the influence of pure bending and lateral force bending on springback of pieces. Maximov et al. (2014) studied the strain hardening and creep behavior of 2024-T3 aluminum alloy at room and high temperature and a power-law temperature-dependent creep model is developed. Moreover, Chen et al. (2016) studied the precipitation behavior of S′ phase in Al-Cu-Mg single crystals during stress-free and stress ageing. Xu et al. (2017a) experimentally investigated the effects of the pre-strain on creep ageing behavior of 2524 aluminum alloy. In views of these reports, all creep ageing temperatures were isothermal. The creep behavior of aluminum alloy under the condition of continuous temperature change is rarely reported. Recently, Xu et al. (2017b) investigated the effect of heating rate on creep ageing behavior of Al-Cu-Mg alloy and found that the creep deformation during the heating process decreases with the increase of the heating rate. Li et al. (2017) developed an unified constitutive model for creep-ageing of an Al-Cu-Li alloy, which has been successfully extended to applications of multistep heat treatments of aluminum alloys. Despite some investigations studied the creep behavior at elevated temperature, the deformation behavior of Al-Cu-Mg alloy under non-isothermal (continuous heating-soaking-cooling) creep age forming condition needs to be systematically investigated for their CAF application.

In this study, the thermal deformation, elastic deformation and non-isothermal creep deformation, as well as springback of Al-Cu-Mg alloy have been investigated using the hot tensile, thermal expansion and creep, as well as creep age forming tests. The heating, soaking and cooling creep deformation with various applied stresses were calculated and discussed, respectively. In addition, creep deformation of the non-isothermal process and the traditional isothermal process were compared. Moreover, the non-isothermal and the isothermal creep age forming tests were carried out to get the springback of Al-Cu-Mg alloy plate. This paper systemically analyzes the deformation behavior during the CAF process, which provides the support for the application of CAF technology.

2. Material and methods

2.1. Materials

The commercial high strength 2524 aluminum alloy was used in this study with the chemical compositions listed in Table 1. The as-received materials are 2.5 mm thick plate with T3 temper provided by Southwestern Aluminum (group) Co., Ltd, China. Both creep tests and tensile tests used the same size of sample. The samples with the gauge length of 50 mm were machined along the rolling direction of the hot-rolled plate, and the geometry and size of the samples are shown in Fig. 1.

2.2. Creep ageing tests

The uniaxial constant-stress creep ageing and hot tensile tests were both carried out on a SUST-D5 creep testing machine with an assisting furnace. The sketch of the creep testing system is shown in Fig. 2. Detailed description of the creep testing system can be found in Xu et al. (2017b) study.

Table 1
Chemical composition of 2524 aluminum alloy (wt%).

Zn	Mg	Cu	Mn	Si	Fe	Ti	Cr	Al
0.01	1.38	4.4	0.66	0.03	0.05	0.03	0.01	Bal.

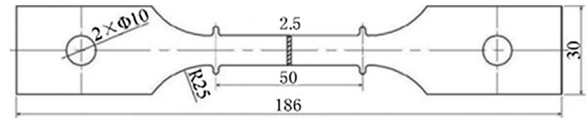

Fig. 1. Specimen geometry and size (unit: mm).

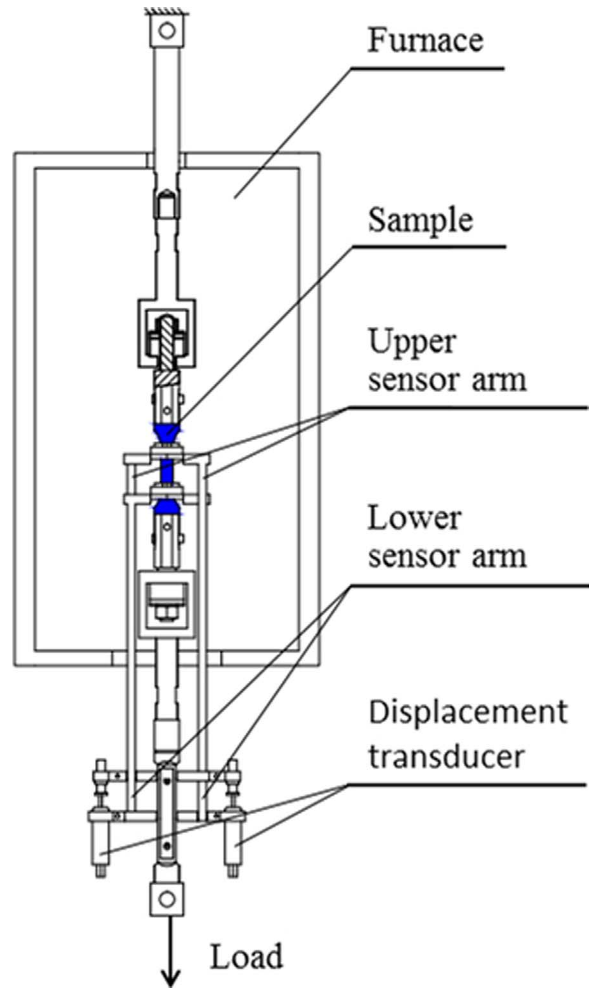

Fig. 2. Sketch of the creep testing system.

The non-isothermal creep ageing tests were carried out for a target temperature of 180 °C for 9 h with a heating rate of 1 °C/min and the samples were naturally cooled in the furnace. The start-temperature and end-temperature was 30 °C and 50 °C, respectively. Three different tensile stresses of 120 MPa, 150 MPa and 180 MPa were selected in this current study, as shown in Table 2. The tensile stress was applied before the heating process and released after the cooling process. Case 1 was carried out to describe the thermal deformation behavior of the studied alloy. The applied stress of 5.5 MPa is a pre-load stress before the creep tests to eliminate the clearance error of the creep testing machine. Case 2–4 were put forward to analysis the non-isothermal creep deformation behavior of the studied alloy. Additionally, the traditional isothermal creep tests (case 5–7) were conducted to compare the creep deformation between the non-isothermal and isothermal creep ageing conditions.

2.3. Hot tensile tests

The hot tensile tests were operated in a wide range of temperatures (30–200 °C). First, the sample was fitted and aligned in the middle of the furnace and thermocouples (K-type; Ni/Al–Ni/Cr) were tied in the