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Stress relaxation behavior of an Al–Zn–Mg–Cu alloy in simulated age-forming process

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ABSTRACT

The stress relaxation behavior of age-forming for an Al–Zn–Mg–Cu alloy was studied using a designed device that can simulate the age forming process. The mechanism of stress relaxation was also revealed through calculating thermal activation parameters and analyzing the microstructures. The results suggested that the stress relaxation behavior of the Al–Zn–Mg–Cu alloy in the simulated age-forming process can be divided into three stages according to the stress level. The three stages of stress relaxation are: (i) the initial high stress stage, (ii) the subsequent middle stress transition stage and (iii) the last low stress equilibrium stage, respectively. The deformation activation energies are 132 kJ/mol in the initial high stress stage, 119 kJ/mol in the subsequent middle stress transition stage and 91 kJ/mol in the last low stress equilibrium stage, respectively. The analysis of the thermal activation parameters and microstructures revealed that dislocation creep was the dominant deformation mechanism in the initial and subsequent stages of the stress relaxation; whereas diffusion creep is the mechanism in the last stage of the stress relaxation. Additionally, a special threshold stress phenomena was present in the stress relaxation of the age-forming process, which was scribed to the interaction between precipitation and dislocation in the Al–Zn–Mg–Cu alloy

1. Introduction

In the past, traditional mechanical forming crafts were showing themselves to be inadequate for manufacturing large integral panel of airplane. To solve this problem, an advanced forming technique named age-forming has been developed. Age-forming is useful for forming accuracy and excellent mechanical properties since it combines mechanical forming and age-hardening, and age-forming has been successfully used to manufacture airplane upper wing skins for a number of years. For example, the upper wing of Airbus A340 air-planes is formed through the age-forming technique, as reported by Jeunechamps et al. (2006). In detail, age-forming can be divided into three steps. Firstly, an elastic loading applies on an aluminum sheet and keeps it full contact with the surface of lower die (loading step). Then, the sheet is held at a specific temperature for an amount of time, in an furnace. During thermal exposure, the age-hardening and stress relaxation due to creep occurs simultaneously in the aluminum alloy (ageing-stress relaxation step). In the ageing-stress relaxation period, the sheet always keeps contact with the surface of lower die. Therefore, the total strain of the sheet keeps constant, and some initial elastic strain has transformed into permanent plastic strain through stress relaxation during the whole thermal exposure period. Finally, the sheet is released and springs back to a shape somewhere between its original shape and the shape of lower die (unloading step). Zhan et al. (2011) summarized that the main advantages of age-forming are the accuracy, repeatability and producing low residual stresses in formed parts. Hence, age-forming abstracted many scholars to research on it. Sallah et al. (1991) built up a mathematical-model of age-forming based on the stress relaxation mechanism, but the physical meaning of this model was not clear. Arabi Jeshvaghani et al. (2012) also pointed out that the fundamental mechanism is the stress relaxation when a age-hardening alloy is artificially aged during age-forming process. Considering the age-hardening of the Al–Cu alloys, Ho et al. (2004a,b) and Jeunechamps et al. (2006) improved the mathematical-model of age-forming and simulated that the whole age-forming process in detail, so that the spring-back after age-forming can be predicted accurately. Besides, age-forming craft of panel components is based on the stress relaxation phenomenon in the artificial ageing process of a metal, which is obviously different from the traditional metal ageing processes. Recently, significant literatures about the influence on microstructure and properties from age-forming have been published. Zhu and Starke (2001a,b) investigated the stress–effect

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on precipitation behavior during the age-forming process, whereas they did not discuss the interaction between stress and precipitates. Bakavos et al. (2006) and Zhu and Starke (2001a,b) reported the mechanical property evolution of aluminum alloys in age-forming, however they did not discuss the interaction between the stress relaxation and age-hardening behavior. The primary objective of age-forming is accurate forming, which depends on the prediction of spring-back after age-forming. The spring-back of panel components is dependent on stress relaxation behavior of metals in age-forming. Before, to investigate the spring-back of panel components in age-forming, many devices have been designed to simulate the whole age-forming process. Quan et al. (2008) developed a 3-point bending test facility to simulate age-forming. The specimen and the test rig are placed in the furnace at an ageing temperature and a constant bending load is applied using a weight. However, Quan's experiment did not perfectly comply the demands of age-forming. The above test was carried out under constant load conditions (similar to creep tests), instead of the stress relaxation conditions encountered in the real age-forming process. Zhang et al. (2008) designed a cantilever bending test device to investigate the stress relaxation for the 2A12CZ Al alloy. That cantilever bending test device would cause a different level of creep deformation or stress relaxation along the length of specimens. Huang et al. (2009) performed an real age-forming tests on an AA2324 alloy, using a constant radius die. Huang found that the initial stress level depends on the thickness of the sheet and the radius of the lower die. In summary, above simple test devices can assess the spring-back of panel components after age-forming, whereas these devices cannot record the stress evolution during the age-forming process. Therefore, above experiments cannot investigate the stress relaxation features of age-forming, which is the key for predicting the spring-back of panel components. In order to obtain a precise spring-back prediction, the stress relaxation mechanism of age-forming needs to be investigated, which is help for the spring-back prediction using a suitable physical model.

On the other hand, it is well known that the stress relaxation is generally regarded as a special creep behavior according to literatures. Solberg (1986) developed a semi-empirical model for simulating stress relaxation using Evans–Harrison universal creep equation, and the simulated results is much accurate. Butt et al. (2000) demonstrated that the intrinsic height of the thermally activable energy barrier evaluated for pure aluminum is of the order of magnitude required for dislocation creep processes, in the stress relaxation test. Besides dislocation creep, Moske et al. (1993) reported that the stress relaxation in pure Al films at a fixed temperature is associated with dislocation creep in the linear part, followed by diffusion creep for a log-time behavior. Even more, stress relaxation behavior can be predicted by established creep laws. In summary, the stress relaxation behavior of pure aluminum has been extensively investigated under constant strain conditions, while to date, hardly any paper has been published on the stress relaxation behavior of high strength aluminum alloys subjected to age-forming. The effect on the stress relaxation from precipitation behavior in high strength aluminum alloys will reduce the accuracy of simulation of age-forming using traditional semi-empirical model.

Based on the above two points, the stress relaxation behavior of age-forming for high strength aluminum alloys is of special interest. In this paper, the stress relaxation behavior of age-forming for an Al–Zn–Mg–Cu alloy was investigated using a designed device. The experiments were designed to simulate the whole age-forming process and the device can completely record the curve of stress–time, which would precisely analyze the stress relaxation feature of an Al–Zn–Mg–Cu alloy in age-forming process.

2. Experimental procedure

2.1. Materials and processing

Cylindrical specimens cut from an Al–Zn–Mg–Cu alloy (5.82 wt%Zn, 2.22 wt%Mg, 2.14 wt%Cu, 0.11 wt%Zr, 0.09 wt%Fe and 0.03 wt%Si) rolled plate with a gauge length of 25 mm and a diameter of 5 mm were tested. The specimens were pretreated at 478 °C for 2 h by solution heat-treatment (SHT) and then water quenched to room temperature immediately. After solution heat-treatment, specimens were subjected to the simulated age-forming (SAF) test at 120 °C, 160 °C and 200 °C using a designed device, respectively. These test temperatures conform to the requirement of the age-forming craft, and they are the classical aging temperatures for the Al–Zn–Mg–Cu alloy, according to references. The designed device is consisted of a universal tensile machine for applying a initial elastic strain on the specimens, a furnace for supplying the aging temperature, a control system for control the loading rate and temperature, a feedback and record system for recording the change of stress during the whole process, as shown in Fig. 1.

The specimens were stretched with a tension load speed of 500 N/S using a universal materials testing machine, until tension load reached 4 kN which kept the total strain of specimens in the elastic strain range. The initial stress loaded on the specimens is 203 MPa, and the stress direction is parallel to the longitudinal direction of the plate. To avoid tension load fluctuation, the specimen was held for a few seconds at the initial tension load until the system keep stable. The whole experiment process is strictly in accordance with the real age-forming process, according to the paper published by Zhan et al. (2011). During the whole SAF process, the tensile displacement of specimens kept constant according to age-forming, so that the total strain was constant. The stress–time curve was recorded by a computer during the whole test process. When the SAF process was finished, the specimen was quickly cooled to room temperature as soon as possible.

Besides, in order to prove the effect of precipitates on stress relaxation of age-forming, two kinds of specimens pre-aged at 120 °C for 6 h and at 160 °C for 24 h, respectively, which can obtain

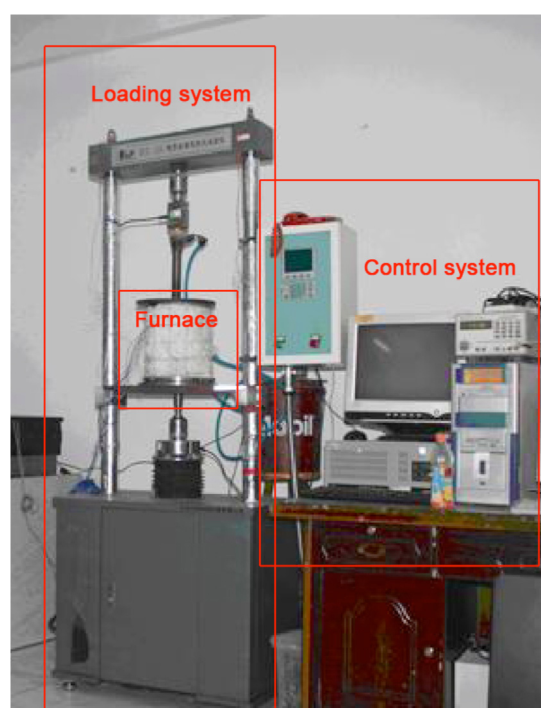

Fig. 1. Schematic diagram of designing system to simulate age-forming (SAF).