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Experimental studies and constitutive modelling of the hardening of aluminium alloy 7055 under creep age forming conditions

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ABSTRACT

A test programme has been designed to characterise the creep-ageing behaviour of Aluminium Alloy 7055, commonly termed AA7055, under creep age forming (CAF) conditions. Creep ageing tests have been carried out for a range of stress levels at 120 °C for 20 h, which is the typical period for a CAF process. Interrupted creep tests have also been carried out to rationalise the effect of stress levels on age hardening. Based on experimental observations, a set of mechanism-based unified creep ageing constitutive equations has been formulated, which models creep induced evolution of precipitates, dislocation hardening, solid solution hardening and age-precipitation hardening. A multiple-step reverse process has been introduced to determine, from creep ageing test data, the values of constants arising in the constitutive equations. Close agreement between experimental data and computed results are obtained for creep and age hardening data for the stress range tested. The determined equation set has been integrated with the commercial FE code MSC.MARC via the user defined subroutine, CRPLAW, for CAF process modelling. In addition to springback, the evolution of precipitate size and creep induced precipitation hardening can be predicted.

1. Introduction

As a relatively new metal forming method, creep age forming (CAF) is advantageous for manufacturing large integrally stiffened lightweight structures in light alloys for the aircraft and aerospace industry, compared to traditional mechanical metal forming methods. Two phenomena (age hardening and creep/stress relaxation) are combined into one in CAF. Ageing is a process that can increase the strength of a metal, while creep during ageing is the mechanism to promote forming and retention of the formed shape of the part. Although some studies have been carried out on creep and ageing as individual processes [1–4], when the two processes are combined, as in CAF, many new problems arise. One of the greatest challenges to improvement of the efficiency of the CAF technique is to predict exactly the amount of springback that will arise, in order that a tool shape may be defined to compensate for it. High levels of springback often result in the formed component being out of tolerance, extra after-work problems during final assembly and also deficient aerodynamic behaviour. Another important feature in CAF is the generation of high mechanical properties in a work-piece. Since usually, CAF is used to manufacture extra large panel components, a trial and error method is costly, laborious and time consuming. Materials and process modelling are efficient ways to understand such problems arising in the new forming method, to accurately predict the ultimate mechanical properties and shape of the tool required for an accurate part to be formed.

To gain an understanding of the mechanism of springback for conventional sheet forming processes, many modelling activities [5–8] on springback prediction for components have been carried out. These are not suitable for CAF, as they contain no consideration of the influence of precipitation hardening on mechanical properties. Less research has been done on the prediction of the ultimate mechanical properties of formed parts in CAF and only Ho et al. [9–10] have published results of a preliminary study on predicting the evolution of mechanical properties of AA7050. A comprehensive material model capable of predicting relationships between forming conditions, microstructure, mechanical properties and springback should be developed to establish a sound scientific basis for CAF processes. In addition to shape production, the most important requirement is to obtain maximum possible values of work-piece mechanical properties through CAF.

Thus to model precipitation hardening and mechanical property evolution of alloys in CAF, it is necessary to derive fully

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determined physically based unified creep ageing constitutive equations.

Some research has been carried out to investigate and establish new constitutive equations for light alloys under CAF conditions and carry out relative process simulation since the invention of CAF. For instance; Sallah et al [11] used a conventional inelastic constitutive equation for autoclave age forming simulation, in which two stress relaxation models (linear Maxwell model and Walker/Wilson model) were used for predicting stress relaxation curves under CAF conditions. Beam specimens were used to experimentally validate the modelling process. Their work provides closed form solutions for age forming simulation of beams using a cylindrical tool and an easy way to determine springback. Guines et al. [12] used a traditional power-law creep model to predict the creep deformation, stress relaxation phenomena, which take place during the thermal exposure (creep-ageing stage) in CAF. A single curved tool was used in the process modelling. The influence of different mechanical clamping conditions on the final shape of a single curvature integrally stiffened structure was carried out. Both these investigations considered only conventional high temperature stress relaxation and/or creep in CAF conditions, while individual physical mechanisms of hardening, such as dislocation hardening, precipitation hardening, during CAF were not modelled.

Ho et al. [9] and Huang et al. [13] used a set of creep damage constitutive equations, developed by Kowalewski et al. [1] to describe creep damage. While two state variables; ϕ, which is related to the over aged condition, and ω_2, which models failure at the tertiary creep stage, were not used in the CAF simulation. These equations have been used mainly to model the basic creep behaviour of metals. However, CAF is a combination of creep deformation and age-hardening, the interaction between them is not considered in their equations, although the equations can be used to predict springback in CAF.

To consider precipitate nucleation, growth and their effects on mechanical property evolution and creep deformation under CAF conditions, Ho et al. [10] developed a set of constitutive equations, which models primary and secondary creep and precipitate nucleation and growth for AA7010 aged at 150 °C. These material models were then introduced into the commercial FE solver ABAQUS through the user defined subroutine CREEP. The increase in yield strength of formed parts was predicted, in addition to the creep deformation, stress relaxation and springback. However, the equation set is only rudimentary as some important process factors such as, the influence of the variation of volume fraction of precipitates, the shape of the precipitates and so on, are not properly considered in them. For example, only one parameter, the radii of precipitates, is used in the equation set to consider the effects of precipitate hardening on creep deformation, thus it is only suitable for spherical precipitates. Further efforts are required to develop mechanism-based creep ageing constitutive equations for aluminium alloys with different forms of precipitates under different CAF conditions.

The work presented in this paper consists of experimental studies and constitutive modelling of creep age hardening of Aluminium Alloy 7055 (AA7055) under CAF conditions. First, the overall experimental programme is introduced and relevant experimental results are analysed. Second a set of mechanism-based unified creep ageing constitutive equations are established based on the experimental observations. Then, a multiple-step reverse process is introduced for determining the values of constants arising in the constitutive equations from creep ageing test data. In the end, the equation set is integrated with the commercial FE solver, MSC.MARC via the user defined subroutine, CRPLAW, for CAF process modelling for a double curvature panel part. In addition to springback, the evolution of creep induced precipitation hardening is predicted.

2. Experimental programme

2.1. Test materials

The material, AA7055, of composition shown in Table 1, used in the experiments was provided in the hot rolled condition. Specimens were machined from sheet of 2.85 mm thickness to a length of 150 mm with a gauge length of 50 mm and then solution heat-treated and water quenched. Subsequently, the samples were kept in a refrigerated condition to reduce natural ageing. The geometry and dimensions of the specimen are shown in Fig. 1.

2.2. The overall test programme

Tests were designed to investigate both creep and ageing behaviour of AA7055 under constant stress for a controlled amount of time (e.g. 20 h) at 120 °C. The tests are very similar to conventional creep tests, apart from the fact that the material used was not artificially aged, but was solution heat-treated and quenched. Therefore, the material was expected to be less strong initially but to exhibit a lot of hardening during the test. The hardening can be attributed to ageing due to thermal exposure and to creep deformation. At the end of the test, the material's yield strength (measured as 0.2% proof stress) was expected to increase due to precipitation and dislocation hardening mechanisms.

Constant stress creep-ageing tests were carried out at 120 °C for the stress range of 190–357.8 MPa. The total test duration was 20 h, which is approximately similar to the duration for a complete industrial creep age-forming process. The experimental procedure, as shown in Fig. 2, can be summarised as follows:

- First, the specimen was fitted and aligned in the middle of the furnace and one additional thermocouple was wired in the middle of the specimen gauge length.
- The furnace was closed and the heating was switched on. Thermal cotton was used to cover the top and bottom of the furnace to reduce heat loss. The closed furnace took up to 1.5 h to rise from room temperature to reach a steady 120 °C.
- When the temperature became steady at 120 °C, a load was applied and the elongation of the specimen was measured.
- The extension was measured every 10 s initially for the first 30 m. The time interval was then increased to 60 s for the rest of the experimental period.
- The data logger was stopped when the time reached 20 h. The heating was switched off, the furnace was opened and the load was removed.

Table 1
Main compositional elements of aluminium alloy 7055, wt%.

Cu	Mg	Zn	Al
2.0–2.6	1.8–2.3	7.6–8.4	Remainder

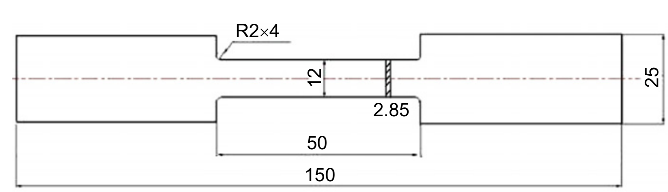

Fig. 1. Specimen geometry (dimensions are in mm).