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Analysis of anisotropic damage in forged Al–Cu–Mg–Si alloy based on creep tests, micrographs of fractured specimen and digital image correlations

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ABSTRACT

The aim of this paper is to analyze anisotropic damage mechanisms in forged Al–Cu–Mg–Si alloy based on the results of creep tests. Smooth specimens are sampled in three forging directions. Creep strain vs. time curves as well as light optical microscope and scanning electron microscope observations illustrate basic features of damage growth. Flat notch specimens are sampled in different directions to analyze stress redistributions and damage in zones of stress concentration. The digital image correlation technique has been applied in situ in order to extract the strain values on the surface of the notched specimens. All observations demonstrate that the principal origins of anisotropic creep and damage are associated with elongated grains and second phase clustered particles located at grain boundaries. Longitudinal specimens possess nucleations of decohesion sites and growth of voids around second phase particles at grain boundaries. Damage evolution for radial and transverse specimens is due to the formation and growth of cracks in second phase particles orthogonal to the principal stress axis. Residual strains are confined to the notch root as well as to the flanges of advanced macrocrack, indicating the small scale yielding during the creep fracture process.

1. Introduction

Age-hardenable AA2xxx alloys based on the aluminum–copper system exhibit superior creep strength and are widely used in structural components operating at elevated temperatures [1,2]. Complex shape parts produced from these alloys usually possess microstructural anisotropy as a result of processing [3]. Furthermore, the creep properties of age-hardenable alloys strongly depend on the heat treatment and ageing conditions [4].

In order to capture hot deformation processes as well as for the analysis of structures operating at high temperature, experimental data for the material response under different loading conditions is required. In addition, analysis of changes in microstructure accompanying deformation, such that coarsening of particles, nucleation and growth of cavities and other processes leading to softening and damage are of primary importance. Experimental data for the creep response as well as data on microstructural evolution are the basis for the development of constitutive models for inelastic deformation. Basic approaches to develop a constitutive model as well as the experimental data required for the identification are discussed in [5–7], for various materials.

Hardening/recovery, ageing and damage processes in aluminum alloys are widely documented in the literature. In [8] a phenomenological model is developed with hardening, ageing and damage parameters to capture creep of the aluminum alloy BS 1742 at 150 °C. A similar model is developed and applied to the analysis of creep age forming processes in [9]. The material parameters are identified for alloys AA2324 and AA7B04. In [10–12] the mean dislocation density and the characteristic particle size are used as internal state variables to characterize Taylor-type dislocation hardening and Orowan-type precipitation hardening mechanisms in various aluminum alloys.

Tertiary creep is usually described by damage, overageing and/or softening variables and corresponding evolution equations. In [13,14] a single damage state variable is utilized to reflect all processes leading to the tertiary creep stage. In [8,9] two independent state variables and kinetic equations are introduced to capture overageing and cavitation processes. A constitutive model

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of anisotropic creep for a forged Al–Cu–Mg–Si alloy is developed in [15] taking into account elongated grains observed in the microstructure. A phase mixture approach is applied to describe stress redistributions in microstructural zones observed for different loading directions. The presence of intragranular strengthening particles is considered and the evolution equation for the normalized particle size is proposed to characterize hardening/recovery and overageing processes.

Experimental data for Al–Cu–Mg–Si alloy including tensile and creep curves for different forging directions are presented in [15,16,4,3]. The aim of this paper is to analyze anisotropic damage mechanisms in Al–Cu–Mg–Si alloy based on the results of creep tests. Smooth specimens are sampled in three forging directions. Creep strain vs. time curves as well as light optical microscope (LOM) and scanning electron microscope (SEM) observations illustrate basic features of damage growth. Flat notch specimens are sampled in different directions to analyze stress redistributions and damage in zones of stress concentration. For a proper design of notched specimens finite element analysis is performed by taking into account anisotropic creep. Creep strength curves are presented to assess the influence of notches on the lifetime. Results of LOM and SEM observations are presented to discuss damage mechanisms in the notch root zone. The digital image correlation (DIC) technique has been applied in situ in order to extract the strain values on the surface of the notched specimens. Time-dependent strain fields are presented to illustrate strain concentrations in the notch zone as well as in the zones confined to fracture surfaces. The results of DIC measurements are compared with those based on the finite element analysis.

2. Experimental details

The material investigated is an Al–4.4Cu–0.5Mg–0.9Si–0.8Mn alloy (IADS 2014 grade). An extruded bar from this alloy was axisymmetrically forged to produce a cave cylinder with the length of 230 mm and an external diameter of 190 mm. Let us designate three directions of a cylindrical forging as follows: the longitudinal (axial) by *L*, the tangential (circumferential) by *T* and the radial by *R*.

2.1. Smooth samples

Al–Cu–Mg–Si alloy forging had displayed anisotropic effects in *L*, *T* and *R* sampling directions [17]. Two sets of 20 × 20 × 100 mm^3 bars were sampled from the as supplied forging with their longer side in *L* and *T* directions, respectively. Tension tests were performed at temperatures within the range 20–170 °C. Creep tests were conducted under constant load at 130 °C, 150 °C and 170 °C (homologous temperature range 0.44–0.49) under stresses that led to a range of times to rupture t_* from several hours to more than 10,000 h. Crept specimens were diametrally cut in order to investigate microstructure features along the gauge length.

2.2. Notched samples

Flat notched specimens were designed according to the type of creep testing machine and the grid system. The lateral dimensions of the specimen including grid parts were limited by the ratio 22 × 35 mm. The gauge width was 14 mm and the notch length was 5 mm. Two values of the notch radii have been chosen as 2.5 and 1.0 mm to reproduce a wide range of stress concentration. The sketch of the specimen with 2.5 mm notch radius is presented Fig. 1. To analyze the anisotropic effects of creep and damage notched specimen were sampled in *L* and *R* directions.

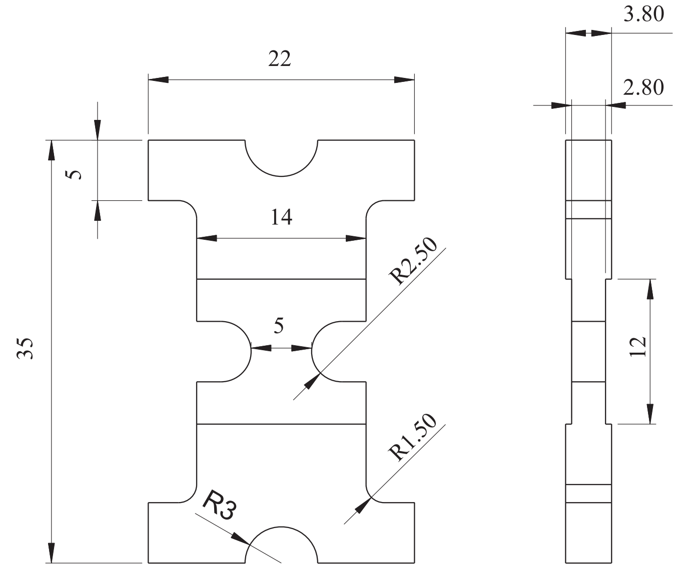

Fig. 1. Sketch of specimen with 2.5 mm notch radius. All dimensions are given in mm.

Notched specimen should be designed to assure that the material creeps at the notch rot and to avoid creep in shoulders. Furthermore, too high stress levels at the notch root would result in excessive deformation outside the power law creep regime, while too low stress values at the beginning and the subsequent stress redistribution would result in a prolonged test duration up to the fracture. For a proper design of notched specimen finite element simulations were performed by varying the geometry and the loading conditions.

One of the flat surfaces of every notched specimen was prepared for microstructural observations with SEM. To this end the notched part was cut from the entire specimen. The outer surface was used for experimental observations, carried out after mounting on the thermosetting resin and mechanical polishing. To reveal the microstructural features such as grain boundaries, precipitates and particles, the specimens were chemically etched with Keller's solution. The etching procedure as recommended for aluminium wrought alloys in [18] was applied.

2.3. Experimental setup for DIC

DIC is a vision-based measurement technique for full field strain estimation. It has been established in 1980s, e.g. Sutton et al. [19] and extensively developed within the last 30 years. In recent years DIC is widely used due to the progress in optical recording technique, promoting the accuracy and quality of acquisition. The basic idea is to compare a digital image of the surface at certain instant of loading with a reference image, taken before the testing. In order to perform a comparison the surface should possess a texture of the natural or artificial origin.

Depending on the imaging devise two types of DIC techniques can be distinguished:

1. 2D based on monocular device,
2. 3D or stereo, using two cameras.

The procedure of DIC consists of the following steps:

1. preparation of the specimen surface (application of texture),
2. image acquisition during the test,
3. digital image processing by means of DIC software to estimate