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Effects of particles and solutes on strength, work-hardening and ductile fracture of aluminium alloys

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ABSTRACT

The influence of particles and solutes on the strength, work-hardening behaviour and ductile fracture of four different aluminium alloys in the as-cast and homogenised condition is investigated in this paper. These alloys contain different types and volume fractions of particles, i.e. constituent particles and dispersoids, in addition to elements in solid solution. Tensile tests on smooth and notched axisymmetric specimens are performed to determine the work-hardening curves and the ductile fracture characteristics of the alloys. A laser-based extensometer is used to continuously measure the logarithmic strain to failure in the minimum cross section of the specimens. Finite element simulations of the test specimens are used to determine the work-hardening curves to failure. Both the J_2 flow theory and the Gurson model are used to describe the stress–strain behaviour of the materials, where the latter accounts for material softening due to void growth. The microstructure of the alloys is characterised by optical and scanning electron microscopy, and fractography is performed to investigate the fracture modes. While the damage and failure mechanisms are similar in the four alloys, the failure strain depends markedly on the stress triaxiality and the yield stress. The trend is that the failure strain decreases linearly with increasing yield stress for the investigated alloys.

1. Introduction

Aluminium alloys are increasingly used in automotive safety components such as bumper beams and crash boxes. In design of these aluminium components, the weight should be minimised without compromising the strength and stiffness, the energy absorption capability and the deformability of the final product, and thus an optimal combination of yield strength, work-hardening and ductility of the material is required. This optimisation process is not trivial, since increased strength is usually obtained at the cost of lowering the work-hardening and the ductility. It was shown experimentally by Lloyd (2003) that for aluminium alloys the tensile fracture strain tends to decrease linearly with increasing yield stress for constant microstructure.

The yield strength of pure aluminium is low (about 10 MPa) and needs to be increased by various strengthening mechanisms. The most relevant strengthening mechanisms for aluminium alloys are solid solution strengthening, increasing the stress field acting upon the dislocations, and precipitation hardening due to shearing and bypassing of particles by dislocations. Yield strength models for age-hardenable aluminium alloys have been proposed by e.g. Deschamps and Brechet (1999) and

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Myhr et al. (2001), where the effects of solute atoms and hardening precipitates are included. Another strengthening mechanism is work-hardening due to the increase of the dislocation density with plastic deformation and the associated evolution of dislocation substructures. Experimental results show that the work-hardening of aluminium alloys at ambient temperature depends on several microstructural features, e.g. solute atoms, non-shearable precipitates, dispersoids and inclusions (Embury et al., 2006). In addition to increasing the yield stress, solute atoms decrease the dynamic recovery rate of dislocations and thus result in higher dislocation density and increased work-hardening rate (Ryen et al., 2006). Hard particles, such as non-shearable precipitates and dispersoids, increase the initial work-hardening rate due to storage of geometrically necessary dislocations around the particles (Cheng et al., 2003; Poole et al., 2005; Zhao et al., 2013; Zhao and Holmedal, 2013a). As stated by Embury et al. (2006), there are two main approaches to the modelling of work-hardening of fcc metals. In the first approach, several internal variables are used to describe the details of the dislocation substructure (e.g. Nes, 1998), while in the other approach the dislocation density is taken as the single internal variable (e.g. Kocks and Mecking, 2003). A work-hardening model for age-hardenable aluminium alloys based on the latter approach was proposed by Cheng et al. (2003), while more recently Myhr et al. (2010) proposed a two-internal-variable model using the statistically stored dislocation density and the geometrically necessary dislocation density as the two internal variables.

The mechanisms controlling the evolution of damage and the ductile fracture of metallic materials are nucleation, growth and coalescence of microscopic voids (e.g. Benzerga and Leblond, 2010). The voids nucleate at constituent particles or inclusions when the stress on the particle is sufficient to induce either particle cracking or particle–matrix decohesion. Continuum models for void nucleation assume that for a given particle size and geometry, the formation of voids depend on the equivalent stress as well as the hydrostatic stress acting on the particle (e.g. Anderson, 2005). Based on computational cell models using the finite element method, it has been established that the void growth and the strain to void coalescence depend on several factors including the initial void volume fraction and the distribution and shape of the voids, the plastic anisotropy, work-hardening and rate sensitivity of the matrix material, and the stress state (Benzerga and Leblond, 2010). Micromechanics-based continuum models for void growth include the Rice–Tracey model (Rice and Tracey, 1969) and the Gurson model (Gurson, 1977) among others. Void coalescence occurs typically by localised plastic deformation and necking of the ligament between adjacent voids. If two classes of particles of different size and spacing are present in the material, void-sheet formation may take place and lead to shear fracture (Teirlinck et al., 1988). Void-sheet formation is caused by nucleation, growth and coalescence of voids at smaller and more densely spaced particles within shear bands linking the larger voids (Anderson, 2005). A limit-load model for void coalescence by internal necking between microvoids was proposed by Thomason (Thomason, 1985a, 1985b). The Thomason model was combined with the Gurson model by Zhang and Niemi (1995) and later with an enhanced version of the Gurson model by Pardoen and Hutchinson (2000). Excellent state-of-the-art reviews of models for ductile damage and fracture based on micromechanics and continuum mechanics are available in Benzerga and Leblond (2010) and Besson (2010).

Traditionally, studies of ductile fracture are based on mechanical testing and microscopy. In recent years, X-ray tomography has made it possible to study the nucleation, growth and coalescence of voids in more details. Maire et al. (2005) performed tomography experiments to investigate the formation and growth of voids in an aluminium matrix containing spherical ceramic particles and used the results to validate an extended version of the Rice-Tracey model. Weck et al. (2008) studied the nucleation, growth and coalescence of voids in a model material with a core/shell design. The core consisted of a pure aluminium matrix with particles, while the shell was made of particle-free aluminium. The results were applied to develop a modified version of the Brown–Embury model (Brown and Embury, 1973) for coalescence. Maire et al. (2011) quantified the damage in three different aluminium alloys using in situ tensile tests in synchrotron X-ray tomography. The results were used to fit the parameters in a modified version of the Rice-Tracey model for void growth and to adapt an existing model for void nucleation. Thuillier et al. (2012) studied the ductile damage in thin sheets of aluminium alloy AA6016-T4 by X-ray micro-tomography and used the Gurson model to analyse the results.

In this paper, the effects of particles and solutes on the strength, work-hardening and ductile fracture are studied experimentally for four aluminium alloys. Two pure Al alloys with different iron content, an AlMn alloy and an AlMgSi alloy were investigated, all in the as-cast and homogenised condition, i.e. without any further heat treatment after homogenisation. The selected alloys contain different types and volume fractions of particles, i.e. constituent particles and dispersoids, and, in addition, the AlMn alloy contains Mn and the AlMgSi alloy contains Mg and Si in solid solution. The solubility of iron in aluminium is low and assumed to have little or no effect on the work-hardening of the alloys investigated. Tensile tests on smooth and notched axisymmetric specimens are carried out to determine the stress–strain behaviour and the ductile fracture characteristics of the alloys. Optical and scanning electron microscopy is used together with fractography to characterise the microstructure of the alloys and to study the damage and fracture mechanisms as function of the stress state. Finite element analysis is combined with the experimental results to determine the work-hardening curves of the materials to failure. In the simulations, both the J_2 flow theory and the Gurson model, which accounts for material softening due to void growth, are used to describe the stress–strain behaviour.

2. Materials

Four aluminium alloys were investigated in this work. The materials were provided as DC-cast extrusion ingots