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Influence of microstructure on work-hardening and ductile fracture of aluminium alloys

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ABSTRACT

The effect of microstructure on the work-hardening and ductile fracture of aluminium alloys was studied using an experimental–numerical approach. Four aluminium alloys with different strength and particle content were tested in uniaxial tension after the following subsequent processing steps: (1) casting and homogenisation, (2) extrusion, and (3) cold rolling followed by heat treatment. The latter processing step was carried out to obtain a recrystallized grain structure with random crystallographic texture. The alloys were two AlFe alloys with different Fe content, one AlMn alloy and one AlMgSi alloy. The grain structure, particle distribution and crystallographic texture were determined for all combinations of alloy and processing route using optical and scanning electron microscopy. Tensile tests were carried out on axisymmetric samples to obtain the true stress–strain curves to failure and the true failure strain of the materials, using a laser-based measuring system. Based on numerical simulations of the tensile tests, the equivalent stress–strain curves were determined to failure, assuming J_2 flow theory. The results showed that the microstructure had a marked effect on both work-hardening and ductility, whilst the ductile fracture mechanism remained unchanged. The plastic anisotropy, induced by the extrusion process and not entirely removed by the cold rolling and heat treatment, led to a wide range of fracture modes of the axisymmetric samples. The failure strain was markedly lower for the cast and homogenised material than for the extruded and the cold rolled and recrystallized materials of the same alloy. The failure strain was further found to decrease linearly with the yield stress for similar microstructure.

1. Introduction

The work-hardening of aluminium alloys is important for the formability of aluminium sheets and profiles and the plastic collapse of aluminium structures [1]. A good description of the work-hardening is further important for the modelling of fracture in aluminium structures, since plastic instability in the form of necking is often a precursor to ductile fracture.

Solute elements, hardening precipitates and dispersoids contribute to the yield strength of aluminium alloys, since they act as distributed pinning points for mobile dislocations, thus increasing the shear stress required to move the dislocations. Solute elements also contribute to an increased work-hardening by reducing the dynamic recovery rate. The work-hardening is further increased by non-shearable hardening precipitates and dispersoids that act as sources for generating geometrically necessary dislocations—the result being a strong work-hardening for small strains. Cheng et al. [2] studied the effect of the precipitation state on the yield stress and work-hardening of two age-hardening aluminium alloys, and developed a semi-empirical model to interpret the experimental results, including contributions to the flow stress from solid solution, precipitation and dislocation hardening. Embury et al. [3] discussed the influence of solute elements, precipitate phases, dispersoids and inclusions, and large strains on the work-hardening of aluminium alloys. A combined precipitation, yield strength and work-hardening model for AlMgSi alloys was developed by Myhr et al. [4], where the influence of solute elements and shearable and non-shearable precipitates on the yield strength and work-hardening was incorporated. Recently, the effect of dispersoids on the work-hardening of aluminium alloys was investigated experimentally by Zhao et al. [5]. The study showed that a fine dispersion of non-shearable particles increased the initial work-hardening and reduced the work-hardening at larger plastic strains. This observation was attributed to the generation of geometrically necessary

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dislocations, and a work-hardening model for aluminium alloys containing dispersoids was proposed.

The ductility of aluminium alloys is influenced significantly by the volume fraction and distribution of intermetallic constituent particles, and in age-hardening alloys also by the precipitate free zones. The constituent particles are large and few compared with the hardening precipitates, i.e., the inter-particle spacing is large, and thus their contribution to the work-hardening becomes limited. Dumont et al. [6] studied the relationship between the microstructure and the strength and toughness of an AA7050 aluminium alloy. The microstructure was varied by changing the quench rate and the ageing time, and the role of the constituent particles, the grain boundary structure and the precipitation state was considered. Morgeneyer et al. [7] investigated void growth and coalescence in an AA2139 aluminium alloy sheet using high-resolution tomography. It was found that as-received and undeformed material exhibited a distribution of elongated voids aligned in the rolling direction, which resulted in toughness anisotropy. A micromechanics-based damage model was used by Steglich et al. [8] to investigate the anisotropic fracture of the 2024-T351 aluminium alloy, taking into consideration the effect of the void aspect ratio and the void distribution. Jordon et al. [9] studied the influence of primary and secondary void nucleation and growth on the ductility of an AA7075 aluminium alloy and used an internal state variable plasticity/damage model to describe the damage-induced anisotropic material response. In the experimental work by Chen et al. [10], dynamic fracture of AA6xxx and AA7xxx aluminium alloys was studied. Partly transgranular and partly intergranular fracture modes were found for all the investigated alloys. The transgranular fracture was promoted by nucleation of voids at primary particles, and possibly dispersoids for the fibrous alloys, whilst the precipitation-free zones along the grain boundaries led to intergranular fracture. Pedersen et al. [11] found similar fracture behaviour in an AA7075-T651 alloys under quasi-static, dynamic and impact loading conditions.

In the present work, an experimental–numerical method was used to determine the large-strain work-hardening and ductile failure strain of four aluminium alloys based on tensile tests on axisymmetric specimens. Using a laser-based measuring system in combination with finite element simulations of the tensile tests, the work-hardening curve of the material could be determined to failure. In a previous study by the authors, this method was used to investigate the work-hardening and ductile fracture of the same alloys in the cast and homogenised condition [12]. The materials investigated were two AlFe alloys, one AlMn alloy and one AlMgSi alloy. In the present study, the method was used to study the influence of microstructure on the work-hardening and ductile fracture of these alloys by subjecting them to different thermo-mechanical processes. Through these processing steps, namely casting and homogenisation, extrusion, and cold rolling and heat treatment, different microstructures were obtained in terms of grain structure, particle distribution and crystallographic texture. The microstructure of the materials and the fracture surfaces were characterised by optical and scanning electron microscopy, whilst the particle and solute element contents were estimated using the Alstruc code [13–15]. The work-hardening of the material was analysed using the extended Voce rule, where two hardening terms were used to capture the various stages of work-hardening. Similar methods have been applied to analyse work-hardening of several commercial aluminium alloys in [1], of AA6111 and AA7030 in [2], of single- and multi-phased aluminium alloys in [3], of AA7108 in [16], and of AA7010 in [17].

2. Materials

The four aluminium alloys studied were provided as DC-cast extrusion ingots of 100 mm diameter produced at the laboratory casting facilities at Hydro Aluminium R&D Sunndal. The chemical compositions of the four alloys, henceforth called Al0.2Fe, Al0.8Fe, Al1.2Mn and AlMgSi, are given in Table 1. TiB was added to all alloys as grain refiner to control the grain size and avoid abnormal grains during casting. In this study, these alloys were mainly selected to investigate the effect of microstructure on the work-hardening and ductile fracture behaviour. However, the Al0.2Fe and Al0.8Fe alloys belong to the AA1xxx series, commonly used for food protection and packaging, the Al1.2Mn alloy belongs to the AA3xxx series, used e.g. in air condition condensers and beverage cans, and the AlMgSi alloy belongs to the AA6xxx series, typically used in the building industry, i.e., window frames and wall panels.

Table 1
Composition in wt% of the four alloys. Grain refiner (TiB) was added to all alloys in order to obtain a homogeneous grain structure.

Material	Fe	Mn	Mg	Si	Al
Al0.2Fe	0.2	–	–	0.05	Bal.
Al0.8Fe	0.8	–	–	0.05	Bal.
Al1.2Mn	0.2	1.2	–	0.05	Bal.
AlMgSi	0.2	–	0.5	0.4	Bal.

Fig. 1 shows the different processing steps after casting to which the materials were subjected. The homogenisation procedures applied to the ingots are compiled in Table 2, and were carried out in a laboratory furnace. The temperature–time cycles are similar to industrial practice and consist of a soaking treatment followed by a predetermined cooling rate. The ingots were further extruded in an 800 tons laboratory press to rectangular profiles with dimensions $10 \times 50\,\text{mm}^2$ and $20 \times 25\,\text{mm}^2$ using industrial extrusion parameters, i.e., billet temperature of 475 °C, container temperature of 435 °C and ram speed of 5 mm/s. The extrusion reduction ratio was 16 in both cases and the profiles were cooled in air. The profile with dimensions $10 \times 50\,\text{mm}^2$ was used for making tensile test specimens. Three specimens with tensile axis in the extrusion direction were machined across the width of the profile for each material. The final processing route was obtained by cold rolling the extruded profile from $20 \times 25\,\text{mm}^2$ to $12 \times 12\,\text{mm}^2$ prior to heat treatment at 500 °C for 5 min and water quenching to achieve a recrystallized grain structure with a texture close to random. The low temperature was used to prevent abnormal grain growth, but it is still above the solvus line for AlMgSi. A similar method was used in [18]. The AlMgSi profile was given a solid solution heat treatment (SSHT) at 540 °C for 30 min followed by water quenching before cold rolling.

After each processing step, the materials were tested after storing them at room temperature for more than one week. The materials obtained after the three processing routes are indicated in Fig. 1 and were named: (1) cast and homogenised (CH), (2) extruded (EX) and (3) rolled and recrystallized (RR)—and these abbreviations will be used henceforth.

3. Experimental–numerical procedures

3.1. Mechanical testing

Triplicate tensile tests were performed on axisymmetric samples respectively oriented along the longitudinal axis of the cast ingot, the extrusion direction (ED) and the rolling direction (RD) for the four materials. The samples had 6 mm diameter and 40 mm parallel length. The average strain rate in the tests was $5 \cdot 10^{-4}\,\text{s}^{-1}$ before necking. The applied force and the diameter at the minimum cross section of the specimen were measured continuously until fracture, using an in-house measuring rig with two perpendicular lasers that accurately measured the specimen diameter (see [12] for details). The Cauchy (true) stress and the logarithmic (true) strain were calculated as