Acta Materialia 131 (2017) 65–76

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Micro-tension and micro-shear experiments to characterize stress-state dependent ductile fracture

Maysam B. Gorji [a], Dirk Mohr [b, *]

[a] Impact and Crashworthiness Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA
[b] Department of Mechanical and Process Engineering, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland

ARTICLE INFO

Article history:
Received 5 November 2016
Received in revised form
17 February 2017
Accepted 15 March 2017
Available online 16 March 2017

Keywords:
Micro-fracture experiments
Ductile fracture
Hosford-Coulomb
Aluminum alloy 6016-T4

ABSTRACT

In view of characterizing the local plasticity and fracture properties in structures with material property gradients at the millimeter scale, a micro-tension and micro-shear testing technique is developed. It makes use of flat dogbone-shaped, notched, central hole and smiley-shear micro-specimens that have been scaled down from their macroscopic counterparts in a way that the critical gage section dimensions do not exceed 500 μm. A new tensile loading device is designed to apply the loading at speed of less than 1 μm/s to achieve strain rate of about 10^{-3}/s at the gage section level. The device includes custom-made clamps without any floating parts that guarantee the alignment of the specimen with respect to the loading axis as well as the uniformity of the applied displacement fields. In-situ experiments on aluminum alloy 6016-T4 are carried out in an optical microscope. Planar digital image correlation is used to compute the surface strain fields. The parameters of the Swift-Voce hardening law and the Hosford-Coulomb fracture initiation model are identified based on the micro-experiments. The obtained material data is validated through numerical simulations of macroscopic fracture experiments that have been performed on the same material.

1. Introduction

Significant progress has been made over the past decade in developing robust experimental techniques to characterize the effect of stress state on the onset of fracture in structures with homogeneous material properties. The tension-torsion technique has been successfully extended from plasticity to fracture characterization [1–4] to provide insight into the effect of the Lode angle parameter in addition to the stress triaxiality. At the same time, new experimental techniques have been put in place to characterize the multiaxial plasticity and stress state dependent fracture initiation in sheet metal. This may be achieved by either varying the combinations of loadings applied onto the specimen boundaries (e.g. Refs. [5–7]) or varying the specimen geometry while applying a uniform axial displacement field onto the specimen boundaries. Candidate specimen geometries for the latter approach include dogbone-shaped, notched or central hole tension specimens (e.g. Refs. [8,9]). Special efforts have been made to come up with flat specimen geometries for characterizing fracture under pure shear which includes single gage section (e.g. Refs. [10–12]) and double gage section [13] shear specimens.

Aside from characterizing the fracture response of polycrystalline materials at the macroscale, i.e. through specimens whose smallest dimensions are still at the millimeter level, there is also a constant quest for experimental results that provide insight into the material response at smaller length scales. This is often motivated by the need to understand the governing failure mechanisms at the grain or sub-grain level (e.g. Refs. [14–18]) and/or by the small dimensions of structures from which the specimen needs to be extracted [19,20]. Mechanical specimens with dimensions of a few microns or even less have been developed for characterizing thin-films [21–24]. In the present work, the downscaling of existing macroscopic experimental techniques is carried out to provide a means to identify the local plasticity and fracture properties in graded materials and structures such as weldments. The latter feature different zones (e.g. fusion zone, heat affected zone, basis material) of approximately constant material properties within regions that are less than 1 mm wide. Micro-hardness testing is often used to characterize the property gradients in metallic structures, but tedious inverse material model parameter identification procedures are needed to extract an approximation of the

* Corresponding author.
E-mail address: dmohr@ethz.ch (D. Mohr).

http://dx.doi.org/10.1016/j.actamat.2017.03.034
1359-6454/

stress-strain curve from such measurements (e.g. Ref. [25]) while no information on the material's fracture response is obtained. To investigate the superplasticity in friction stir processed Al-Mg-Zr alloy, miniature tensile specimens of 0.5 mm thickness and 1.3 mm gage length have been tested by Ma et al. [26] using a custom-built mini tensile tester. Peel et al. [27] made use of Vickers hardness measurements and tensile tests on flat dumbbell specimens with gage section dimensions of 2.6 × 12.5 × 50 mm to characterize the mechanical response of friction stir welded aluminum 5083. In their experiments, the strain fields have been determined using electronic speckle pattern interferometry with a 780 nm laser, providing a spatial resolution of 20–100 μm. Their results demonstrate that the recrystallized weld zone exhibits a significantly lower hardness and yield stress than the base material. Genevois et al. [28,29] extracted 25 mm long micro-tensile specimens featuring a 0.8 × 4 mm cross-section from welded aluminum 2024 plates using electro-discharge machining. They also performed macro-tensile experiments and demonstrated that the local tensile curves obtained through strain mapping agree reasonably well with the results from micro-tension experiments.

In the present work, a new experimental technique is proposed to perform tension experiments on miniaturized dogbone-shaped, notched and central hole specimens whose maximum gage section width does not exceed 500 μm. At the same length scale, a micro-smiley specimen is also proposed for characterizing the fracture response for stress states close to pure shear. In-situ experiments are performed on aluminum alloy 6016-T4 under an optical microscope to determine the displacement and strain fields through digital image correlation of microscopy images. Subsequently, the Swift-Voce hardening law and Hosford-Coulomb fracture initiation model parameters are identified using a hybrid numerical-experimental approach. In addition, conventional macroscopic fracture experiments are performed to validate the obtained "micro" material model parameters through simulations of macroscopic experiments.

2. Experimental procedures

2.1. Material

All specimens are extracted from aluminum alloy 6016-T4 sheets of 1.5 mm nominal thickness. This heat-treated Al-Mg-Si sheet material has been provided by the manufacturer after requesting an isotropic sheet material. Fig. 1 shows representative EBSD pictures of the polycrystalline microstructure. In the plane of the sheet, the average grain size is 50 μm with an aspect ratio of 1.6 (Fig. 1a). In the RD-TD plane, i.e. the cross-sectional plane that contains the rolling and thickness directions, the average grain size is 37 μm with an aspect ratio of 1.5 (Fig. 1b). In view of minimizing microstructural changes due to machining, all specimens are extracted using a combination of micro wire-EDM cutting and CNC micro-milling.

2.2. Micro-specimens

A typical basic plasticity and fracture testing program for sheet materials includes dogbone specimens for uniaxial tension (UT specimens), flat specimens with symmetric circular cut-outs (NT specimens), flat specimens with a central hole (CH specimens) and in-plane shear specimens (SH specimens). In view of characterizing the fracture response of structures with property gradients at the millimeter level, we design micro-specimens with cross-section dimensions of less than 500 μm by downscaling the macro-specimens proposed by Dunand and Mohr [9] and Roth and Mohr [13].

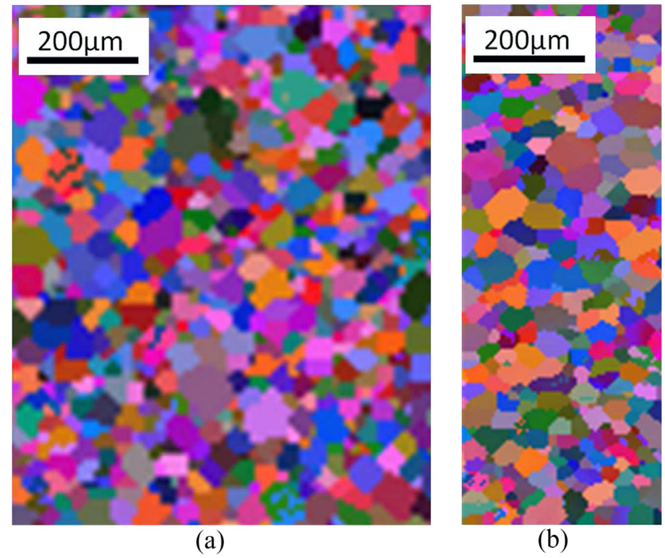

Fig. 1. EBSD images showing the grain morphology: (a) plane of the sheet, (b) cross-sectional view with the thickness direction being parallel to the vertical direction.

Fig. 2 shows the resulting micro-specimen drawings. The in-plane specimen dimensions are typically scaled down by a factor of about 20× (from macro to micro), while a thickness of 200 μm is chosen for all specimens to provide sufficient bending stiffness for specimen handling. With regards to the smallest specimen dimension, it is worth noting that the μ-specimens featured about six grains along the thickness directions. Given that both the grain size analysis and micro-hardness measurements did not reveal any noticeable property gradient in the thickness of the sheet, we did not make any special effort to verify the exact location of specimen extraction after receipt of the specimens. A micro wire EDM with a wire diameter of 50 μm is employed to extract the specimens from the aluminum sheets. After an initial slicing operation, the 2D specimen contours are cut. An under-sized hole is first introduced into the μ-CH specimens using sinker EDM, before it is enlarged to a nominal diameter of 400 μm using wire EDM machining. The gage section widths of the micro-specimens are 500 μm for the μ-UT, μ-NT and μ-SH specimens, and 300 μm for the μ-CH specimen. The total length of the first three specimen types is about 7.5 mm. The μ-SH is almost twice as long which is due the required strength for the specimen shoulders.

2.3. Micro-testing device

A micro-testing device is designed to load the above specimens under static loading conditions all the way to fracture. The specimen gripping and alignment is the most sensitive part of the entire testing procedure which led us develop a custom-made device instead of using a commercialized system. Simple limit analysis revealed that the maximum expected force for the micro-specimens is about 30N. In the uniaxial tension experiments, the initial yield point is expected to be attained after applying a displacement of $130/70000 \times 1.5\ \text{mm} \cong 3\ \mu\text{m}$. Furthermore, preliminary FE analysis revealed that fracture may be expected in all specimens at displacements ranging from 100 μm to 500 μm. To obtain a strain rate of the order of 10^{-3}/s, the displacement needs to be applied at a rate of the order of 1 μm/s. Given the above design considerations, we chose the following components for the micro-testing device (Fig. 3a):