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Effect of microstructure on strain localization in a 7050 aluminum alloy: Comparison of experiments and modeling for various textures

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ABSTRACT

Microstructure attributes are responsible for heterogeneous deformation and strain localization. In this study, the relation between residual strain fields and microstructure is examined and assessed by means of experiments and crystal plasticity modeling. The microstructure of rolled aluminum alloys (AA) in the 7050-T7451 condition was experimentally obtained with electron backscatter diffraction (EBSD) analysis along the rolling direction (L-T orientation), across the rolling direction (T-L orientation), and transverse to the rolling direction (T-S orientation). Each of these sections was also patterned using a novel microstamping procedure, to allow for strain mapping by digital image correlation (DIC). The measured microstructures were in turn used as input of an elasto-viscoplastic crystal plasticity formulation based on fast Fourier transforms (EVP-FFT). Comparisons between the strain maps obtained experimentally by the concurrent DIC-EBSD method and the EVP-FFT simulations were made for the three sections, corresponding to the initial textures. The comparisons showed that the predicted levels of strain concentration were reasonable for all three specimens from a statistical perspective, which is important to properly describe and predict the strains within an ensemble of components; however the spatial match with the actual strain fields needs improvement.

1. Introduction

Aluminum alloys play an important role in the modern transportation industry, due to their combination of weight, strength, ease of manufacture, and environmental resistance. In worldwide aviation, aluminum alloys are present in more than two thirds of the plane's dry weight, still being the preferred material for an aircraft's primary structures. It means that the majority of the load carrying components and fatigue critical locations are made of this material, which are frequently stressed in multiple directions and under complex loading conditions. Component failure is a result of deformation accumulating in small regions within a part. In fact, strain localization is a precursor to material failure. Understanding the strain localization and the role of microstructure, *e.g.* grain's orientation and boundaries, on the strain energy accumulation is a key factor for improving the application of such materials under aggressive loading and environments. In this paper, the investigation of strain localization is enabled through combined experimental analysis and material's modeling, the outcomes of which are explored and compared.

In polycrystalline materials, the microstructure attributes are responsible for heterogeneous deformation. The presence of grains and grain boundaries tends to localize deformation. Digital image correlation (DIC) has become a valuable technique to study local strain in materials and components through non-contact/non-destructive analysis. Additionally, electron backscatter diffraction (EBSD) is the predominant technique to identify spatial maps of local grain orientations. In recent years, microstructural information has been coupled with local strain maps by means of concurrent DIC-EBSD. For example, Tschopp et al. performed in-situ strain mapping in a scanning electron microscope (SEM) of a Ni-base superalloy, Rene 88DT [1]. Clair et al. used kernel average misorientation to investigate local strain near triple points [2]. Abuzaid et al. used DIC-EBSD to investigate polycrystalline deformation [3]. In this case, an *ex-situ* technique was used at 31 × magnification to investigate a large area of interest (1 mm by 0.8 mm). The results were analyzed using Taylor model, to identify the individual slip systems that accommodated plastic deformation. Carter et al. performed DIC in an SEM at elevated temperatures to study grain boundary sliding mechanisms [4]. Kammers and Daly analyzed deformation in ultra-fine grain material with significant contributions to state-of-the-art speckle patterns and biasing and calibrations necessary for the quantification of strain fields obtained from DIC within an SEM [5]. Da Fonseca et al. used

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a novel speckle pattern technique achieving slip level resolution in their strain maps [6]. Esquivel and Sangid have used DIC-EBSD technique within a SEM to resolve the strain accommodated within individual slip bands [7].

Elasto Viscoplastic crystal Plasticity (EVP) links the applied macroscopic load and micro-mechanical response, accounting for slip activation. Experimental strain maps have been recently compared with crystal plasticity simulations. Using an oligocrystal aluminum sample, Zhao et al. suggested that grain topology and micro-texture have significant influence on the origin of strain heterogeneity [8]. Turner et al. carried out a detailed comparison between DIC (enabled by individual strain gauges produced by focus ion beam providing fiducial marks on the specimen surface) and model predictions, and pointed out the wide variation in mechanical behavior produced by the subsurface microstructure [9]. Further, Tasan et al. used similar comparisons between modeling and experiments on dual phase steels to identify hot spots of damage at locations of larger ferritic grains and lower local martensitic fractions [10]. Lim et al. concluded that EVP model predictions agree reasonably well at various applied strains in tantalum oligocrystals [11]. In the present work, various orientations of highly textured, rolled Al plate are characterized and compared with EVP simulations performed with direct input from microstructural images using an FFT-based model framework. The work demonstrates the EVP-FFT method accurately reproduces the statistical nature of heterogeneous deformation of the various configurations, but cannot capture the exact strain localization at individual microstructure features.

2. Material and method

2.1. Material

A plate of 7050 aluminum alloy (AA) received in the T7451 condition with nominal composition [12] was used in this study. Three specimens were machined from the plate, with a length of 48 mm in the following directions: parallel to the rolling direction of the plate (L-T); perpendicular to the rolling direction, with the width aligned with the long direction (T-L); and perpendicular to the rolling direction, with the width aligned with the short (thickness) direction (T-S), as shown in Fig. 1. All the specimens were 1.6 mm thick and machined 6.4 mm away from the plate surfaces to avoid the excessive effect of the rolling process. The specimen geometry was adapted from the ASTM E8 [13] standard, to better serve the purpose of the DIC characterization. The geometry of specimens chosen for the present study was based on the size of the surface to be analyzed and compatible dimensions with the SEM chamber.

2.2. Experimental procedures

All tension experiments were conducted at room temperature (23 °C), following the basic procedures described in [13]. For the DIC experiments, the specimens were polished on 1200 grit sand paper for 2–3 min or until all machining marks were completely removed. One side of each specimen was then polished for 40 min using a NAPAD with 0.05 μm blue colloidal silica, or until a mirror-like surface was obtained. After final polishing, the area of interest was properly marked (using fiducial indents) in the center of the specimen [14], as depicted in Fig. 2. For placing the markings on the specimen, the automated LECO Microhardness Tester LM247AT was used. The two center indents were obtained with 1 N of indentation force, and the four smaller indents in each side defining the areas of interest were obtained with 0.5 N. Each area of interest was defined by fiducial markings in a rectangle of 800 μm by 600 μm.

An FEI Philips XL-40 SEM was used for EBSD characterization. The average grain size was 80 μm, and typically ranging from 30 to 500 μm, depending on the specimen orientation with respect to the alloy rolling direction. For DIC patterning, the specimens were stamped using a novel micro stamp, manufactured by 1900 Engineering LLC, designed for the DIC reference patterning [15]. Details of the flexible micro textured stamps are outlined in [16]. A master is first created by lithography or another manufacturing method; here an e-beam lithography (EBL) process is used to create a 10 μm base-element size for generating the stamp over a 12.7 mm × 12.7 mm area, with a speckle population of 22%. Then a castable material is selected, which should conform to sub-micron features in the master, yet should be sufficiently flexible to release from the master during the demolding step without damaging the master. The castable material is polymerized, and so the polymerization chemistry must be selected to avoid bonding to the master itself. The material is vacuum cast to the master, expelling all entrapped gas and allowing the material to flow into the sub-micron features in the master. The castable material polymerizes

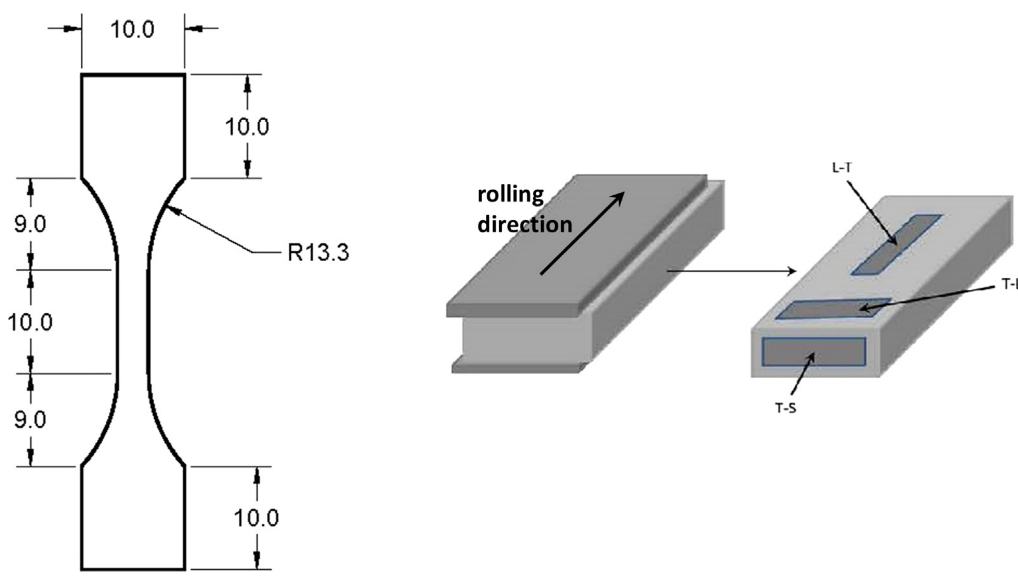

Fig. 1. Specimen geometry and orientations from AA 7050-T7451 plate (dimensions in mm). Each specimen had a length of 48 mm and a thickness of 1.6 mm.