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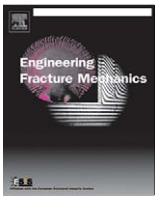

Microstructure and texture evolution during the drawing of tungsten wires

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ABSTRACT

Tungsten wires develop during their forming process a pronounced fibre texture that causes anisotropic deformation of single grains. The aim of this work is to simulate the crystallographic texture and microstructure evolution that arises during wire drawing using two different texture models. A visco-plastic self-consistent model that allows simulations using a large number of grains is compared with a crystal plasticity finite element model that provides a more detailed insight into the wire's microstructure. Texture predictions of both models are discussed and quantitatively compared with experimental texture measurements obtained by neutron diffraction. The developed fibre texture causes plane strain deformation of single grains, which induces grain curling. The prediction of grain curling is of importance because it allows studying the residual stresses that trigger splits, at the grain level.

1. Introduction

Tungsten wires for bulb filaments are produced from sintered rods, whose diameter is reduced by rolling and swaging down to few millimetres. Swaged tungsten wires are then drawn in successive steps until they reach a diameter suitable to be used as lamp filaments, typically about 40 μm. During the drawing process the wires undergo severe plastic deformation that drastically changes their microstructure. Grains elongate in the axial direction and establish a pronounced $\langle 011 \rangle$ fibre texture. Textured grains deform by plane strain elongation [1,2]; consequently, initially equiaxed grains tend to develop an elongated ribbon shape. The ribbon-shaped grains need to bend around each other in order to accomplish the macroscopic deformation, creating a characteristic pattern in the cross-section of the wire, known as *grain curling* or *Van Gogh sky structures*.

The heterogeneous strain distribution at the microscopic level produces locally high stress concentrations that might explain the tendency of bcc wires to develop longitudinal intergranular cracks (Fig. 1) known as splits [3–5]. This is, by far, the less understood fracture mechanism that occurs during the drawing of tungsten wires [6]. Therefore, stress localization at grain boundaries and second-order residual stresses are of very high importance. The optimization of drawing process parameters hence, requires the knowledge of material behaviour at the microstructural level.

In this work we simulate the drawing process using two different models. As a first approach, we apply the visco-plastic self-consistent model (VPSC) proposed by Lebensohn and Tomé [7]. The second model used is a crystal plasticity based finite element model (CPFEM).

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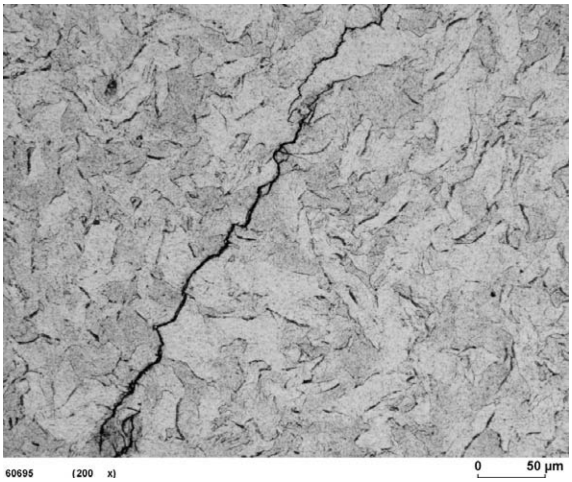

Fig. 1. Cross-section of an etched tungsten wire showing an intergranular crack.

VPSC has proved to be a valuable tool for predicting texture and microstructure evolution under different loading conditions. For instance, it has been extensively used for simulating microstructure evolution and texture development during equal channel angular extrusion of fcc [8–11] and bcc metals [12]. The feasibility of VPSC for simulating the wire drawing process has also been explored. Bolmaro et al. [13] simulated texture development and microstructure evolution during drawing of Cu–Fe wires. They performed calculations using Taylor and VPSC models and the texture components obtained from the simulations were compared with neutron diffraction measurements. VPSC, as a stand alone code, is computationally less expensive when compared to CPFEM and allows using a larger number of grains in the simulation. VPSC can also be used in conjunction with finite elements [14].

CPFEM provides a more accurate insight into the heterogeneities of the material, since it fully accounts for grain to grain interaction. Accordingly, the model is able to predict complex morphological microstructures, intra- and intergranular stresses and texture development. However, the computational power available nowadays restricts the application of CPFEM to a few grains. CPFEM was used by Očenášek et al. [15] for simulating the wire drawing process. The simulations were able to reproduce the observed curled microstructure of drawn tungsten wires and the preference of single grains to orient themselves towards the $\langle 011 \rangle$ direction. Gil Sevillano et al. [16] applied strain gradient crystal plasticity to a similar model with a larger number of grains to study the internal stresses at the grain level that arise during the drawing process. They found large tensile stresses acting on the $[100]$ direction as a consequence of the plane strain deformation of individual grains caused by the developed $\langle 011 \rangle$ texture. The presence of tensile stresses may explain the tendency of bcc metals to fail by splitting.

In what follows, Section 2 presents neutron diffraction measurements on tungsten wires. The experimental setup is briefly explained and the results of the measurements discussed. This experimental data is used throughout the paper for comparison with the simulation predictions. Section 3 introduces the models used for the drawing simulations and is subdivided in two subsections. The first one is devoted to the visco-plastic self-consistent model. The second one deals with the CPFEM model. Simulations of the wire drawing process are presented in Section 4. The results obtained with VPSC and CPFEM are explained and discussed in Sections 4.1 and 4.2, respectively. Their predictions are analyzed and quantitatively compared with the experimental measurements. Finally, the most important results are recalled and summed up in Section 5.

2. Experimental results

Tungsten rods are sintered from tungsten ore and processed as a first step by rolling. They are then swaged until a diameter suitable to be drawn is reached. The material used in this study consists of as-received swaged and drawn potassium doped tungsten wires, commonly used in the lighting industry. We selected wires of three different diameters (Table 1):

Table 1
Sample notation.

Sample A: D_0
Sample B: $0.72D_0$
Sample C: $0.32D_0$