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MODELING EVOLUTION OF ANISOTROPY IN PEARLITIC STEEL DURING COLD WORKING

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Summary. Simulated evolution of anisotropy by reorientation of cementite lamellae in pearlitic steel is compared to experimental data. The modeling of reorientation and the homogenization of the yield function are discussed

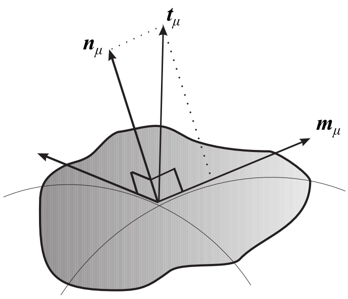
1 INTRODUCTION

Predicting Rolling Contact Fatigue (RCF) in the rail-wheel contact is a key research topic within the railway industry. The costs of RCF damages are very high, and thus the economic benefit of optimizing the maintenance schedule is large. The evolving anisotropy, due to accumulating plastic deformation in the surface layer, is believed to greatly influence the RCF life. A clear directional dependence on impact toughness after tests on railway wheels has been shown[1]. Additionally, it has been found that a rail's anisotropic properties control whether cracks grow downwards and potentially cause rail breakage, or turn upwards and create relatively harmless chips[2].

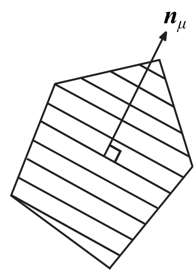
A constitutive model utilizing areal affine reorientation[3] of the cementite lamellae in pearlitic steel has been proposed by Johansson and Ekh[4]. The model was developed further in Larijani et al[5], and applied to High Pressure Torsion (HPT) tests in Larijani et al[6]. In addition to HPT, several other methods exist to achieve large plastic strains, such as equal channel angular pressing, wire drawing and cold rolling. In this contribution we evaluate the modeling of reorientation during these methods. In particular, the effects of modifying the areal affine assumption are investigated.

2 MODEL OF EVOLVING ANISOTROPY

In Larijani et al[5], the yield function is based on shearing of the ferrite along the surface of cementite lamellae. A scalar stress measure τ_μ of Schmid type is adopted, where the shear direction $\boldsymbol{m}_\mu$ is determined by the projection of the stress tensor on



(a) Vectors on the cementite lamella



(b) Pearlitic structure

Figure 1: Definitions of pearlite structure and directions

the cementite lamella (defined by the normal vector $\boldsymbol{n}_\mu$):

$$\tau_\mu(\boldsymbol{\tau}_\mu, \boldsymbol{n}_\mu, \boldsymbol{m}_\mu) = \boldsymbol{m}_\mu \cdot \boldsymbol{t}_\mu = \boldsymbol{m}_\mu \cdot (\boldsymbol{\tau}_\mu \cdot \boldsymbol{n}_\mu), \quad \boldsymbol{m}_\mu = \frac{\boldsymbol{t}_\mu - t_\mu \boldsymbol{n}_\mu}{|\boldsymbol{t}_\mu - t_\mu \boldsymbol{n}_\mu|}, \quad t_\mu = \boldsymbol{t}_\mu \cdot \boldsymbol{n}_\mu \tag{1}$$

The yield function is composed of τ_μ in (1) and a von Mises part $\tau_{vM\mu}$ according to

$$\Phi_\mu(\boldsymbol{\tau}_\mu, \boldsymbol{n}_\mu, \boldsymbol{m}_\mu) = \frac{\zeta \tau_\mu^2 + (1-\zeta)\tau_{vM\mu}^2}{Y_\mu} - Y_\mu, \quad \tau_{vM\mu} = \sqrt{\frac{3}{2}\boldsymbol{\tau}_\mu^{\text{dev}} : \boldsymbol{\tau}_\mu^{\text{dev}}} \tag{2}$$

Motivated by this micromechanical yield function Φ_μ, a macroscopic yield function Φ is formulated by using homogenization via integration over a unit sphere:

$$\begin{aligned} \Phi &= \frac{\frac{15}{2}\left[\text{tr}\left(\boldsymbol{A}\cdot\boldsymbol{\tau}^2\right) - \boldsymbol{\tau} : \mathcal{B} : \boldsymbol{\tau}\right] + (1-\zeta)\tau_{vM}^2}{Y} - Y \\ \boldsymbol{A} &= \langle \boldsymbol{A}_\mu \rangle = \langle \boldsymbol{n}_\mu \otimes \boldsymbol{n}_\mu \rangle, \quad \mathcal{B} = \langle \boldsymbol{A}_\mu \otimes \boldsymbol{A}_\mu \rangle \end{aligned} \tag{3}$$

The Schmid part of the equation is scaled by 15/2 so that a von Mises response is obtained for randomly distributed $\boldsymbol{n}_\mu$. Note that the brackets $\langle\bullet\rangle$ denote the homogenization of $\bullet$ over the unit sphere.

The development of anisotropy is modeled by letting the set of normal vectors $\boldsymbol{n}_\mu$ undergo an areal affine reorientation[3] based on the macroscopic deformation gradient $\boldsymbol{F}$:

$$\boldsymbol{n}_\mu = \frac{\boldsymbol{F}^{-T}\boldsymbol{n}_{\mu 0}}{|\boldsymbol{F}^{-T}\boldsymbol{n}_{\mu 0}|} \tag{4}$$

3 WIRE DRAWING

In the wire drawing process the wire is fed through a series of dies with decreasing diameter. Using this method a tensile strength in pearlitic close to 7 GPa has been achieved, at an engineering strain of 678[7]. The engineering strains in relation to the diameter reduction ratio are:

$$\varepsilon_{11} = \left(\frac{d_0}{d}\right)^2, \quad \varepsilon_{22} = \varepsilon_{33} = \frac{d}{d_0}, \quad \varepsilon_{\text{ij}} = 0,\ i \neq j \tag{5}$$

Here a uniform deformation is assumed, and x_1 is the drawing direction.

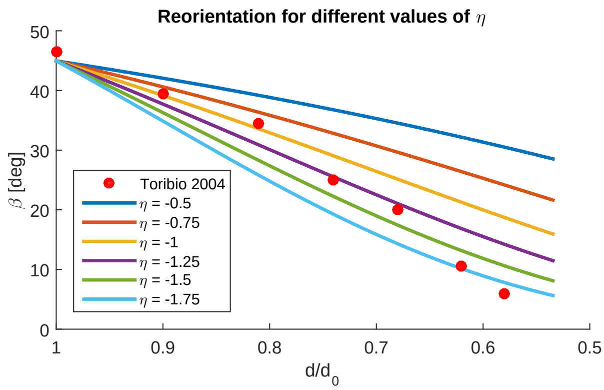


Figure 2: Orientation angle[8] β of the microstructure for different values of η.

4 REORIENTATION OF CEMENTITE

In the model by Larijani et al[5] an areal affine reorientation is assumed according to equation (4). This equation can be reformulated as a rate equation for the cementite normal vector $\boldsymbol{n}_\mu$ as follows[3]:

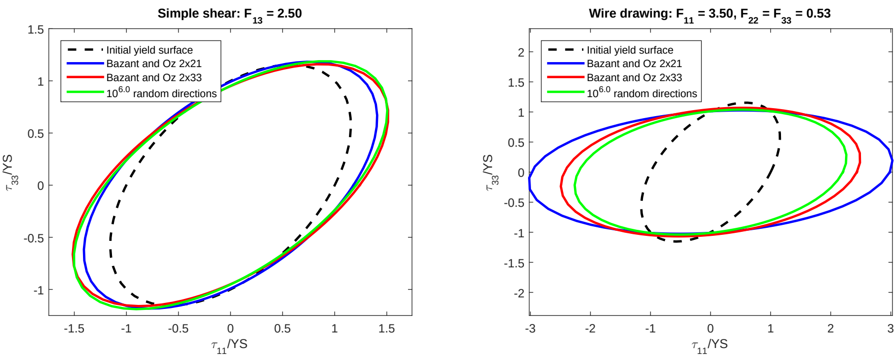
$$\dot{\boldsymbol{n}}_\mu = (\boldsymbol{W} - \boldsymbol{W}^p)\,\boldsymbol{n}_\mu, \quad \boldsymbol{W}^p = \eta\left[(\boldsymbol{n}_\mu \otimes \boldsymbol{n}_\mu)\boldsymbol{D} - \boldsymbol{D}(\boldsymbol{n}_\mu \otimes \boldsymbol{n}_\mu)\right] \tag{6}$$

Here $\boldsymbol{D}$ and $\boldsymbol{W}$ are the symmetric and skew part of the velocity gradient $\dot{\boldsymbol{F}}\boldsymbol{F}^{-1}$, respectively. It turns out that setting $\eta = 1$ corresponds to affine orientation and $\eta = -1$ to areal affine orientation. In the current study, η is treated as a model parameter. Experiments on the reorientation of cementite in pearlite during wire drawing has been performed in literature[8]. In order to evaluate if η should be modified from the areal affine assumption, the reorientation predictions are compared with the experimental data in Figure 2. From these results it can be concluded that, for large strains, $\eta = -1.5$ matches the experimental data better than the areal affine assumption. The model qualitatively predicts the reorientation, but no accurate prediction over the entire strain range is achieved for any value of η.

5 NUMERICAL INTEGRATION OVER UNIT SPHERE

The numerical method used to homogenize over the unit sphere may, in addition to the reorientation of the cementite lamellae, significantly influence the results. If the sphere is discretized using a uniform grid of Euler angles, the point density will increase towards the poles. This will therefore not be an efficient numerical integration scheme. Bažant and Oh[9] proposed several symmetric schemes that utilize head to tail symmetry to integrate over a sphere surface, using a combination of directions and weights similar to Gauss points. The influence of a 2x21 and a 2x33 integration scheme is shown in Figure 3. The yield surfaces (defined by equation (3)) in the $\tau_{22} = 0$ plane are compared after simple shear $F_{12} = 2.5$ and wire drawing $F_{11} = 3.5$. In the figures the yield functions based on homogenization of a million randomly distributed $\boldsymbol{n}_\mu$ are also shown as reference.

For the simple shear case the influence of the integration technique is less pronounced than for the wire drawing case. Even so, the integration technique influences



(a) Simple shear

(b) Wire drawing

Figure 3: Yield surface after deformation

the results in both cases and requires further investigation.

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