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Simulation of high pressure torsion tests of pearlitic steel

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ABSTRACT

High pressure torsion (HPT) is a severe plastic deformation (SPD) method that can transform the characteristic lamellar microstructure of pearlitic steel to a severely deformed and aligned microstructure with respect to the deformation direction. In the current paper, HPT experiment results for the standard rail grade R260 were utilised to calibrate a material model formulated for large deformations to predict evolution of anisotropy due to microstructural changes in pearlitic steel. The HPT deformation procedure is simulated in the commercial Finite Element (FE) package ABAQUS. Numerical results agree well with experimental data demonstrating the high potential of the proposed material model in analyses including large deformations of pearlitic steel, e.g. in railway applications and Rolling Contact Fatigue (RCF) analyses.

1. Introduction

Pearlite with its composite-like structure of ductile ferrite and high-strength cementite is the base, or a substantial structural constituent, of many high-strength steels. Steels with pearlitic microstructures are according to Garnham and Davis (2009) well suited and utilized for high-strength wire applications and also in railway components. Large irreversible deformations in these pearlitic steel components are inevitable either during manufacturing and/or in service. Therefore the behaviour of pearlitic steel when subjected to large deformations has been the subject of many research studies. For wire applications, an early example is Langford (1977) where the strength of wire drawn pearlitic steel versus the interlamellar spacing and the lamellae orientation was analysed. Other examples are Toribio and Ovejero (1998) where the decrease of interlamellar spacing during cold drawing was studied and Toribio (2004) where also the lamella re-orientation was measured. Furthermore, the importance of the cementite lamellae alignment and their decrease of thickness during wire drawing was studied in Zhang et al. (2010).

Although an aligned and fine grained microstructure of pearlitic steel can be achieved in wire drawing tests the loading condition is not very close to the rail–wheel contact where high compressive stresses are combined with large shear stresses. High Pressure Torsion (HPT) as a severe plastic deformation (SPD) process is a well established technique that can produce a microstructure similar to that found in the plastically deformed surface layer of rails while imposing a very similar loading condition to that of the rail–wheel contact. Due to the high hydrostatic pressure applied during this type of torsion test the fracture strain is increased and extremely large torsional deformations can be imposed to the specimen, as discussed already by Bridgman (1943). Some studies on changes of mechanical properties of railway materials under large plastic deformations have been carried out with the help of HPT tests. In Hohenwarter et al. (2011) the change of fracture toughness as a function of pre-deformation up to an equivalent von Mises strain of approximately 17 was studied and it was found that the fracture toughness became anisotropic due to alignment of the pearlitic structure. Similar results but for higher strains (up to shear strain 28) were achieved in Kammerhofer et al. (2013).

Zhilyaev and Langdon (2008) proposed that, depending on the shape of the anvil and as a result conditions imposed on the outward flow in the sample, HPT tests are divided in two distinct types: unconstrained and constrained. Simulation of unconstrained high pressure torsion process has been the subject of a few studies where the main focus are on the obtained inhomogeneous stress-strain field and contact conditions between the sample and the anvils. In Kim (2001) HPT of pure copper up to 72° torsion was analysed using isotropic elasto-plasticity and FEM in ABAQUS with axisymmetric elements with twist. A 3D FE model using rigid-plasticity in the code Deform was used in Yoon et al. (2008) to study the obtained inhomogeneous strain field of a nanostructured material up to two revolutions. A polymer was studied in Draï and Aour (2013) with a 3D model in the FE software MSC Marc up to torsion angle 60°. In

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Verleysen et al. (2013) a semi-constrained HPT is simulated utilising remeshing techniques in the commercial FE package ABAQUS. Strain gradient plasticity models were used in Estrin et al. (2008) to predict dislocation cell sizes and dislocation densities for copper assuming a given stress distribution in constrained HPT specimen.

In this work HPT tests of the pearlitic rail grade R260 are modelled using the same axisymmetric finite element formulation as in Kim (2001). The HPT tests have been carried out at Erich Schmid Institute of Materials Science. Tensile samples are prepared from the pre-deformed HPT discs and tensile tests are performed whereby the influence from pre-deformation is obtained. The purpose is to show the behaviour of severely deformed surface layer of rails. To take into account the alignment of the pearlitic structure, a hybrid micro-macromechanical material model proposed in Larijani et al. (2013) is used in the simulations. The model is formulated for large deformations and use the multiplicative decomposition of the deformation gradient. The evolution of anisotropy, which is governed by re-orientation of cementite lamellae, is assumed to be of areal-affine type, cf. Dafalias (2001). The model parameters are identified from the tests of the tensile samples of the pre-deformed HPT discs. The capability of the model to mimic and predict experimental result will show its usability in simulations of rail-wheel contact situations.

In this work the deformation procedure of an HPT disk sample is modelled utilizing a two dimensional model in the commercial FE package ABAQUS and the material model proposed in Larijani et al. (2013) as a material subroutine. The corresponding experiments have been carried out at Erich Schmid Institute of Materials Science. Results from uniaxial tension tests of samples pre-deformed in the HPT machine, are employed to calibrate the material model.

The paper is organized as follows: In Section 2 the HPT experiments and the following tensile tests are described. The adopted constitutive model is briefly described in Section 3. FE simulations and the calibration procedure are described in Section 4 and the corresponding results are presented and discussed in Section 5.

2. High pressure torsion tests

The HPT experiments were carried out at Erich Schmid Institute of Materials Science on the standard rail grade R260 and constituted of two stages. In the first stage samples were extracted from the gauge corner at a depth of approximately 10 mm. Subsequently discs with a diameters of 25 mm and a thickness of 8 mm were machined from the samples and deformed in the HPT tool under a pressure of 4 GPa at ambient temperatures. The applied torsion consisted of a torsional shearing of the upper surface corresponding to (1/4), (1/2) and 2 revolutions. In order to have the full stick condition at the contact surfaces while applying the torsional load, the anvil and sample surfaces were sandblasted. The resulting equivalent von Mises strain ϵ_{vM} due to torsional loading can be approximated by a linear function of the radius, r and the angle of torsion, φ:

$$\epsilon_{\mathrm{vM}} = \frac{r\varphi}{t\sqrt{3}}, \tag{1}$$

with t being the thickness of the disk. The HPT deformation leads to a transformation of the initial colonial pearlite to a nanostructured pearlite, with lamellae aligned in the direction of shear deformation. At a degree of deformation with $\epsilon_{\mathrm{vM}} \approx 4$ the largest part of the structure is aligned and further deformation results in increased refinement of the structure (decrease of the interlamellar distance and thinning of the lamellae). The evolution of the microstructure with increasing degree of deformation together with the microstructure of the base material can be seen in Fig. 1.

After the HPT pre-deformation, tensile samples were prepared from the disc at various radii, with the sample axis being parallel to the shear direction, as illustrated in Fig. 2.

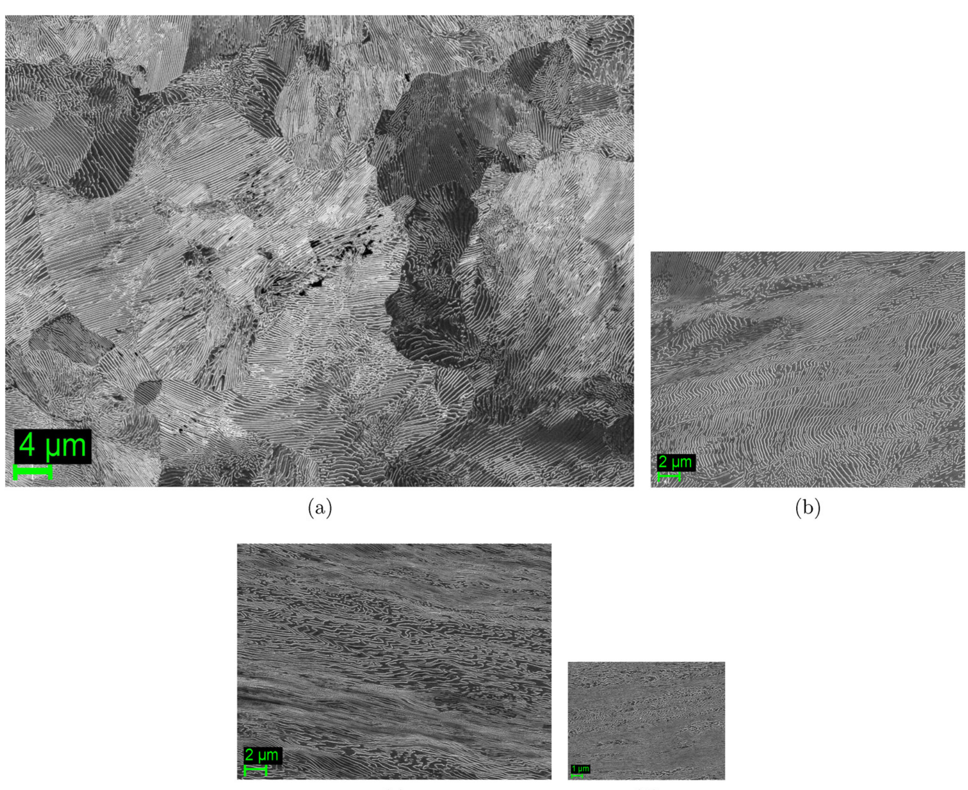

Fig. 1. SEM micrographs of pearlitic steel R260 at (a) $\epsilon_{\mathrm{vM}} = 0$ (base material); (b) $\epsilon_{\mathrm{vM}} \approx 1$; (c) $\epsilon_{\mathrm{vM}} \approx 3$; (d) $\epsilon_{\mathrm{vM}} \approx 5$.