Materials Science & Engineering A 560 (2013) 273–277

Contents lists available at SciVerse ScienceDirect

Materials Science & Engineering A

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

Quantification of local and global elastic anisotropy in ultrafine grained gradient microstructures, produced by linear flow splitting

Jörn Niehuesbernd [a,*], Clemens Müller [a], Wolfgang Pantleon [b], Enrico Bruder [a]

[a] Division of Physical Metallurgy, Materials Science Department, Darmstadt University of Technology, Petersenstraße 23, 64287 Darmstadt, Germany
[b] Department of Mechanical Engineering, Section of Materials and Surface Engineering, Technical University of Denmark, Produktionstorvet 425, 2800 Kgs, Lyngby, Denmark

ARTICLE INFO

Article history:
Received 7 August 2012
Accepted 19 September 2012
Available online 2 October 2012

Keywords:
EBSD
Steel
Sheet forming
Orientation relationships
Elastic anisotropy

ABSTRACT

Severely deformed materials often show strong plastic strain gradients, which can lead to a variety of gradients in microstructure and texture. Since the elastic behavior of a material is in most cases linked to its crystallographic texture, gradients in the elastic properties are also possible. Consequently, the macroscopic elastic behavior results from the local elastic properties within the gradient. In the present investigation profiles produced by the linear flow splitting process were examined with respect to local and global elastic anisotropy, which develops during the complex forming process. The local grain orientations determined by EBSD measurements were used to calculate the elastic tensors at several positions along the strain gradient. Based on the geometric mean, the calculated local elastic constants were transferred into global ones by appropriate weighting. Ultrasonic measurements were carried out to determine the macroscopic stiffness tensor of the severely deformed parts, showing a good agreement with the global stiffness tensor calculated from orientation data.

1. Introduction

The steadily increasing expenses for energy and raw material led to several developments in product and material design during the last few decades. Components are expected to show an increased strength and stiffness, while simultaneously being produced with less material usage and less production costs. An elegant way to increase the stiffness, while reducing the material usage and thus reducing the weight, is to use bifurcations. Linear flow splitting (LFS) offers the possibility to produce bifurcated structures integrally with low production costs, even while using high strength materials. Linear flow split profiles are well suitable as stiffening elements or, owing to the low surface roughness of the produced flanges, as linear guides [1]. Linear flow splitting induces severe plastic deformation at the edge of a sheet, using obtuse angled splitting rolls [2]. The edge is being broadened so that a bifurcation is produced after several steps (see Fig. 1a). As depicted in Fig. 1b, the material flow is perpendicular to the feed direction, thus the direction from the splitting center to the flange tip can be identified as the rolling direction (RD) (see Fig. 1c). Consequently the feed direction corresponds to the transverse direction (TD) and the direction from the flange top to the bottom surface is the normal direction (ND). Unlike established severe plastic deformation (SPD) processes like equal channel angular pressing (ECAP), high pressure torsion (HPT) or accumulative roll bonding (ARB), which are characterized by inducing severe strains while almost maintaining the initial dimensions of the work piece [3,4], linear flow splitting leads to significant changes in the geometry. Thus, strictly speaking LFS cannot be categorized as a SPD process in the narrower sense. Nevertheless it imposes severe strains and produces an ultrafine grained (UFG) microstructure in a surface layer [5]. The process zone is less defined than in the previously mentioned SPD processes and exhibits steep strain gradients [6], leading to strong microstructure and yield strength gradients in the flange thickness direction [7]. Earlier investigations using electron backscattering diffraction (EBSD) have shown that the crystallographic texture also varies along with the other gradients [8]. Due to the severe plastic deformation and the distinct property gradients, it is reasonable to assume, that the Young's modulus exhibits an anisotropic and heterogeneous character as well. Consequently, elastic material properties obtained by conventional experimental methods (for example tensile tests) could deviate significantly from the local elastic properties within the microstructure gradient, since the measured values would only be averages over the flange thickness. However, for special applications it is important to determine the microscopic elastic properties more precisely. Additional roll forming or the application of the profiles as linear guides requires the previous evaluation of the process layout and the rolling contact fatigue using FEM simulations. In order to obtain most accurate simulation results, it is essential to have an exact knowledge of the local elastic properties and the potential

* Corresponding author. Tel.: +49 6151 165594; fax: +49 6151 165557.
E-mail address: j.niehuesbernd@phm.tu-darmstadt.de (J. Niehuesbernd).

0921-5093/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.msea.2012.09.067

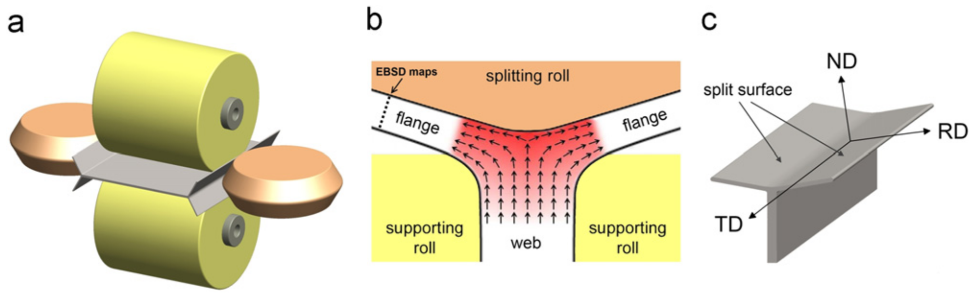

Fig. 1. (a) Function principle of linear flow splitting, (b) material flow in the process zone and (c) chosen coordinate system.

gradient within the flanges. The calculation of the elastic parameters using orientation data obtained by EBSD can be carried out with the well-established methods proposed by Voigt and Reussin [9]. Voigt used the assumption of spatially constant strains within the material, while Reuss proposed constant stresses. The results of these calculations are upper and lower bounds, within which the actual values have to lie. The grain orientations at every discrete measurement point obtained by EBSD can be used to determine rotation matrices (T), which rotate the single crystal stiffness (C) and compliance (S) tensors for all points (N) of the measurement grid. The polycrystal stiffness and compliance tensors after Voigt (C_V) and Reuss (S_R) can then be calculated as follows [10]:

$$C_V = \frac{1}{N}\sum_i^N [T_i]^T[C][T_i] \tag{E1}$$

$$S_R = \frac{1}{N}\sum_i^N [T_i{}^T]^{-1}[C]^{-1}[T_i]^{-1} = \frac{1}{N}\sum_i^N [T_i{}^T]^{-1}[S][T_i]^{-1} \tag{E2}$$

Since the Voigt and Reuss approximations can be considered as upper and lower bounds, an additional approach is needed, which describes the actual elastic properties more precisely. Hill proposed a simple arithmetic mean of the approximations calculated after Voigt and Reuss, namely the Voigt–Reuss–Hill average (VRH) [11]. This approach is often sufficient for the description of the elastic properties. Nevertheless it has some detrimental characteristics. The tensor inversion of C_V leads to a tensor which differs from S_R and vice versa. So there are four ways of calculating an arithmetic mean, with slight differences from each other. In contrast, the concept of the geometric mean offers the possibility of calculating stiffness and compliance tensors, which lie within the Voigt and Reuss bounds [12] and can be transferred into each other via proper tensor inversion. In most cases the geometric mean provides similarly accurate approximations of the actual elastic properties as self-consistent approaches, but with substantially less calculation effort [13]. The calculation routines are analog to Voigt and Reuss, except for the additional calculation of the natural logarithm of the stiffness and compliance tensors before averaging [14]:

$$C_{geom} = \exp\left(\frac{1}{N}\sum_i^N \ln([T_i]^T[C][T_i])\right) = \left[\exp\left(\frac{1}{N}\sum_i^N \ln([T_i{}^T]^{-1}[S][T_i]^{-1})\right)\right]^{-1} \tag{E3}$$

2. Experimental

All investigations were carried out on a high strength low alloy steel (H480LA) with the following chemical composition (wt%): 0.07 C, 0.688 Mn, 0.039 Nb, 0.033 Al, 0.029 Si, 0.012 P, 0.003 S. The thickness of the initial sheet was 2 mm. The microstructure of the as received material consists of ferrite grains and small Fe_3C particles (1 vol%) located at the grain boundaries. Linear flow splitting was carried out continuously in 10 stages and led to flanges with lengths of 12 mm and a thickness of about 1 mm. For texture and microstructure investigations cross sections of the double-Y-profiles were prepared using standard metallographic grinding and polishing techniques followed by an additional polishing step with an aqueous suspension of 0.05 μm Al_2O_3 particles. EBSD measurements were carried out with an FEI XL30 FEG scanning electron microscope at approximately half the distance from the splitting center to the flange tip, in 25, 50, 100, 200, 400, 600 and 1000 μm underneath the split surface, i.e. from the split surface to a position close to the lower surface (see Fig. 1b). These were used for calculation of the texture and the elastic anisotropy at the respective position, according to Eqs. (E1–E3). The elastic constants of single crystal iron, with C_{11}=230 GPa, C_{12}=134 GPa and C_{44}=116 GPa were used for the crystallographic stiffness tensor C [15]. The size of the EBSD maps was chosen in a way that at least 1000 grains could be found within, to ensure sufficient statistics. Orientation distribution functions (ODF) were calculated using harmonic series expansion with a series rank of 24, a Gaussian half width of 5° and the assumption of orthotropic symmetry. All grid points with a confidence index above 0.1 were used for both, the texture and the Young's Modulus calculations.

Ultrasonic runtime measurements were performed on the flanges in addition to the EBSD measurements. Based on sound velocities obtained by the pulse–echo method, the elastic parameters were calculated using Greens formulas [16]. Transversal and longitudinal transducers with frequencies of 5 and 10 MHz were used, with glycerin as couplant for longitudinal waves and honey for transversal waves. Samples were prepared out of the flanges in rolling direction (RD), transverse direction (TD) and normal direction (ND), as well as under 45° between RD and TD, under 25° and 65° between RD and ND and under 25° and 65° between TD and ND. The diagonal components of the stiffness tensor C_{11}, C_{22}, C_{33}, C_{44}, C_{55} and C_{66} were determined from the samples cut along the main directions (RD, TD, ND). The components C_{12}, C_{13} and C_{23} were obtained from sound velocity measurements on the samples cut out between the main directions.

3. Results and discussion

Due to the fact that the strains at the split surface are much larger than at the center or the lower side of the flanges, a strong microstructural gradient develops in flange thickness direction, as shown in Fig. 2 exemplarily for 25 μm and 600 μm underneath the split surface. In association with a significant decrease in grain aspect ratio, the grain dimensions in flange thickness direction increase from less than 0.1 μm in the near surface UFG regions to approximately 1 μm at the lower surface of the flanges. Along