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Modeling of the inhomogeneity of grain refinement during combined metal forming process by finite element and cellular automata methods

Janusz Majta, Łukasz Madej, Dmytro S. Svyetlichnyy, Konrad Perzyński, Marcin Kwiecień *, Krzysztof Muszka

AGH University of Science and Technology, Mickiewicza 30, 30–059 Krakow, Poland

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ABSTRACT

The potential of discrete cellular automata technique to predict the grain refinement in wires produced using combined metal forming process is presented and discussed within the paper. The developed combined metal forming process can be treated as one of the Severe Plastic Deformation (SPD) techniques that consists of three different modes of deformation: asymmetric drawing with bending, namely accumulated angular drawing (AAD), wire drawing (WD) and wire flattening (WF). To accurately replicate complex stress state both at macro and micro scales during subsequent deformations two stage modeling approach was used. First, the Finite Element Method (FEM), implemented in commercial ABAQUS software, was applied to simulate entire combined forming process at the macro scale level. Then, based on FEM results, the Cellular Automata (CA) method was applied for simulation of grain refinement at the microstructure level. Data transferred between FEM and CA methods included set of files with strain tensor components obtained from selected integration points in the macro scale model. As a result of CA simulation, detailed information on microstructure evolution during severe plastic deformation conditions was obtained, namely: changes of shape and sizes of modeled representative volume with imposed microstructure, changes of the number of grains, subgrains and dislocation cells, development of grain boundaries angle distribution as well as changes in the pole figures. To evaluate CA model predictive capabilities, results of computer simulation were compared with scanning electron microscopy and electron back scattered diffraction images (SEM/EBSD) studies of samples after AAD+WD+WF process.

1. Introduction

Extensive research on development of strong and yet ductile ultrafine-grained (UFG) or nanomaterials, that may be produced in a continuous manner, resulted in a new group of the products, where the microstructural features are organized in clusters or layers. In the present study, the influence of combined effects of area reduction, bending, shearing and burnishing on the accumulated deformation energy and microstructural inhomogeneities in the metal forming products are studied by numerical simulations to evaluate possibilities of formation of ultrafine-grained and multilayered structures in subsequently flattened wires.

With the recent progress in computing power including (among others) high performance computing and parallelization for multicore CPU (Central Processing Unit) and GPU (Graphical Processing Unit) computing, the complexity of numerical models can be significantly increased. Thus, there has been a rapid development of complex, but time consuming modeling methods e.g. Cellular Automata (CA). This method is considered as a very useful and universal tool for modeling and simulation of microstructural changes and has already been applied to simulate various microstructural phenomena - see authors' earlier works e.g. [1–7] In the case of very time consuming simulations, also a modified version of the classical cellular automata called Frontal Cellular Automata method can be used [1–4]. Possibilities of application of the latter one to modeling microstructure evolution under very complex deformation states occurring during the investigated combined metal forming operations is investigated in the present work.

* Corresponding author.
E-mail address: mkwiecie@agh.edu.pl (M. Kwiecień).

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2. Combined metal forming process and the microstructure analysis

The combined metal forming process investigated in the present study can be effectively applied in the production of ultrafine-grained wires with several similarities to the Severe Plastic Deformation (SPD) processes [8–10]. As a case study for the present investigation microalloyed steel wire rods (diameter of 6.5 mm) were analyzed, with a basic chemical compositions being (in wt%): 0.07C/0.29Si/1.36Mn/0.067Nb/ 0.03Ti/0.16Cu/0.0098N/0.002B. The wire rods were supplied with recrystallized polygonal ferrite microstructure having mean grain size equal to 15 μm. The production process of UFG and multilayered material was carried out according to the general sequence as follows. First, accumulative angular drawing (AAD) process [11–14] was performed to introduce severely deformed and inhomogeneous microstructures in the drawn wires. In this process, three passes of deformation were applied and final wire diameter after AAD was 4.0 mm. Total strains of 0.45 and 0.37 were applied in the first and second pass, respectively, followed by the calibration pass with the strain of 0.14 (ε_T=1.43). Although, the AAD design allows for various combinations of die positioning, the present study was concentrated on the stepped die alignment, in which the offset from the drawing line between successive dies was equal to 10°. Additionally, after each pass, the wire was rotated by 120° to obtain axisymmetrical distribution of strain accumulation at the cross-section of a final product. Next, a multi-pass linear wire drawing (WD) process was carried out until wire diameter was reduced to 1.96 mm. Finally, produced wires were additionally deformed by wire flattening (WF) with equivalent strain of 0.42 to the thickness of 400 μm, so that the total strain accumulated in all processes was ε_T=2.86. Sample produced by mentioned complex deformation schedules was subjected to microstructure analysis and mechanical testing.

Application of the complex deformation modes (AAD+WD+WF), instead of typical wire drawing (WD), and proper control of the level of accumulated deformation energy and microstructural inhomogeneity result in the improvement of both strength and ductility in the investigated microalloyed steel. Mechanical properties measured in the tensile tests clearly show that by applying the combined metal forming processing (AAD+WD+WF) indicative enhancement of strength of the microalloyed ferrite specimens was observed [15,16]. It is also evident, that in the final product of this combined forming process i.e. in flattened wire, more significant grain refinement was noticed in the layers close to the specimens' surface (Fig. 1a) with comparison to the central layers (Fig. 1b).

For investigated in the present study microalloyed steel, effects of precipitation and solid solution strengthening indicatively influence the microstructure development [9,17]. Also, deformation mechanisms, as a function of the grain size and accumulated deformation energy, significantly change in the microalloyed ferrite during the combined metal forming processing. It has already been proved, that when the grains are refined to the nano-size level, the main deformation goes along grain boundaries. Hence, when the bimodal microstructure is produced, as it can be observed in the present study, the deformation conditions are improved due to the two deformation mechanisms, i.e. in the grain boundaries and the grain interiors. Additionally, as it has already been presented in [18] and also is shown in Fig. 1, the grain size, distribution and crystallographic orientations are clearly different in the different locations of cross section of the flattened wires. It is observed that inhomogeneity of the microstructure development, first of all the progress of grain refinement, is the

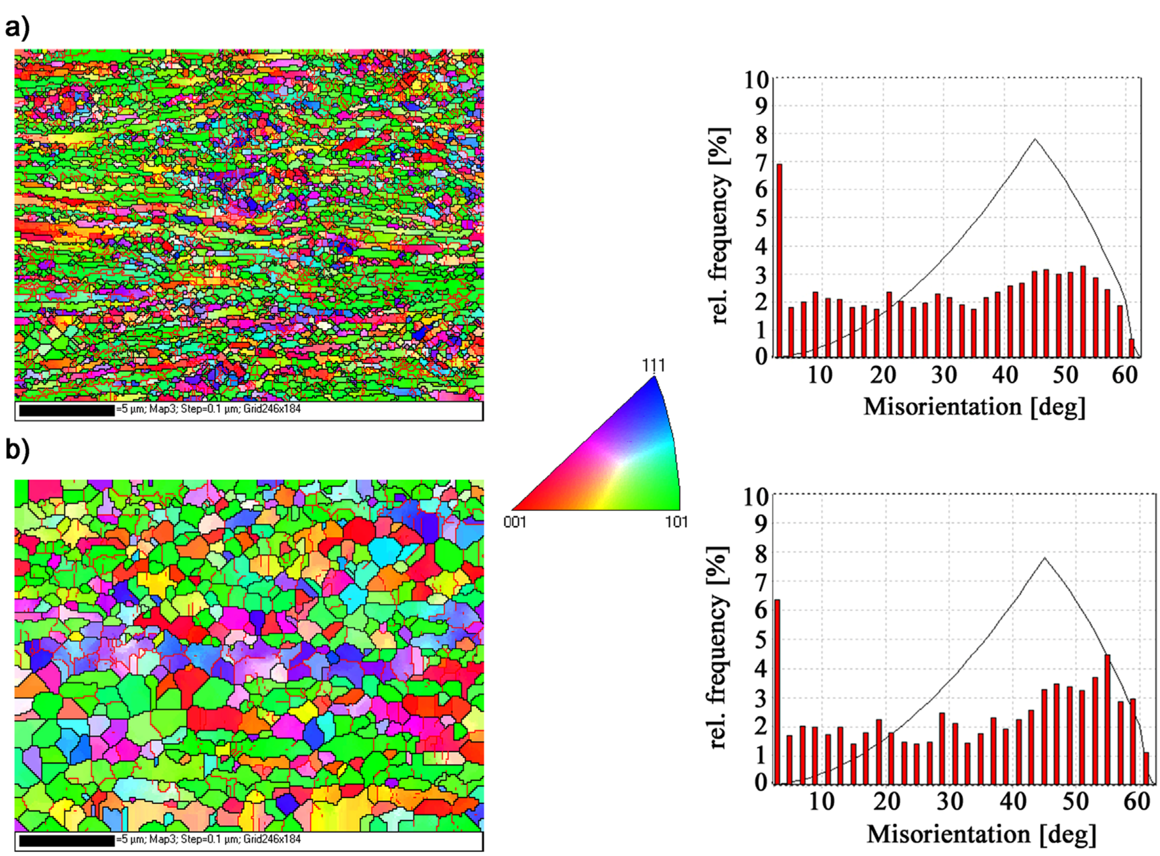

Fig. 1. EBSD results showing maps of grain boundaries at the cross section of the studied material obtained after combined AAD+WD+WF processing. Microstructures taken in the areas close to the surface (a), and the center (b) of deformed material.