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APPLICATION OF THE THREE DIMENSIONAL DIGITAL MATERIAL REPRESENTATION APPROACH TO MODEL MICROSTRUCTURE INHOMOGENEITY DURING PROCESSES INVOLVING STRAIN PATH CHANGES

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Abstract

The present paper discusses possibilities of application of the 3D Digital Materials Representation (DMR) approach in the light of the multiscale modelling of materials subjected to the complex strain paths. In some metal forming processes, material undergoes complex loading history that introduces significant inhomogeneity of the strain. High strain gradients, in turn, lead to high inhomogeneity of microstructure and make the prediction of the final material's properties especially complicated. Proper control of those parameters is very difficult and can be effectively optimised only if the numerical tools are involved. The 3D Digital Materials Representation approach is presented and introduced in the present paper into a multiscale finite element model of two metal forming processes characterised by high microstructural gradients: the cyclic torsion deformation and the Accumulative Angular Drawing (AAD). Due to a combination of the multiscale finite element model with the DMR approach, detailed information on strain inhomogeneities was obtained in both investigated processes.

Key words: 3D digital material representation, multiscale modelling, strain path changes

1. INTRODUCTION

During manufacturing processes, metal may be subjected to complex strain path changes that introduce high level of both deformation and microstructural inhomogeneity and make the prediction of material behaviour extremely difficult. Existing numerical tools are powerful and offer various possibilities, however there are still limitations in the modelling of processes that are characterised by non-linear and non-symmetrical deformation modes. Problem of strain path change on the microstructure evolution and mechanical behaviour has been widely studied, both theoretically and experimentally (Davenport et al, 1999; Jorge-Badiola & Gutierrez, 2004). It has been found that this processing parameter significantly retards recrystallization, precipitation and phase transformation kinetics during hot deformation of steels. Strain path changes applied during cold deformation also play important role in the control of strain and microstructure inhomogeneity. High local strain accumulation leads to significant grain refinement and significantly improves strength of the material but in some cases (severe plastic deformation methods) decreases ductility of the material. Understanding of the strain path in the light of aforementioned problems is therefore of paramount importance.

Computer modelling needs to be involved in order to learn how to control the microstructure and

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deformation inhomogeneity during complex loading processes. Due to nonlinearity and lack of symmetry, simulation of deformation involving complex strain path changes requires 3D models to be created. As most of the microstructural phenomena during deformation take place at various scales, multiscale modelling approach should also be considered. Proper representation of the microstructural features can be effectively done with utilisation of the recently developed Digital Materials Representation (DMR) (Madej et al., 2011) technique, where microstructure is explicitly represented by properly divided heterogeneous finite element mesh.

In the present paper, the 3D Digital Materials Representation approach is presented and incorporated into a multiscale finite element model of two metal forming processes characterised by high microstructural gradients. The first case study involves cyclic torsion deformation of the FCC structure, whereas in the second case study, Accumulative Angular Drawing (AAD) process of the BCC structure is modelled.

2. EXPERIMENTAL INVESTIGATION

2.1. Forward/reverse torsion test

The effect of strain reversal on austenite subjected to strain path reversal was studied in torsion using model alloy system with a chemical composition of 0.092C-30.3Ni-1.67Mn-1.51Mo-0.19Si (in wt. %). Since in Fe-30wt%Ni systems austenite phase is stable down to room temperature and they are characterised by similar Stacking Fault Energy and high temperature flow behaviour as low carbon steels, they are widely used to model the austenite phase of those materials. The initial microstructure of the studied material represented by EBSD map is shown in figure 1. Solid bar torsion specimens with gauge length of 20mm and gauge diameter of 10mm were machined out of the solution treated plate. Torsion test was carried out using servo-hydraulic torsion rig at 840ºC with strain rate of 1/s. Two deformation routes were applied, both with the same equivalent total strain of 2. In the first case, 4 cycles of forward/reverse with strain of 0.25 per pass (8-passes in total) were applied. In the second case, 2-passes of deformation with the strain of 1 per pass and only one reversal were applied.

Deformed microstructures observed using optical microscopy are shown infigure1 b, c. It can be seen that in both cases, the original shape of austenite grains has been restored. In the case of 2-pass deformation, however, the initial austenite microstructure has been subdivided into well-developed lamellar structures separated by high angle grain boundaries (Sun et al., 2011). The recorded flow curves are summarized in figure 2. In both cases, the strain level upon reversal is lower what suggests occurrence so called Bauschinger effect – due to rearrangement of the substructure upon reversal the dislocation density in the reversed structure is lower. Additionally, based on the flow curves it can be seen that this effect has been multiplied in the 8-pass test.

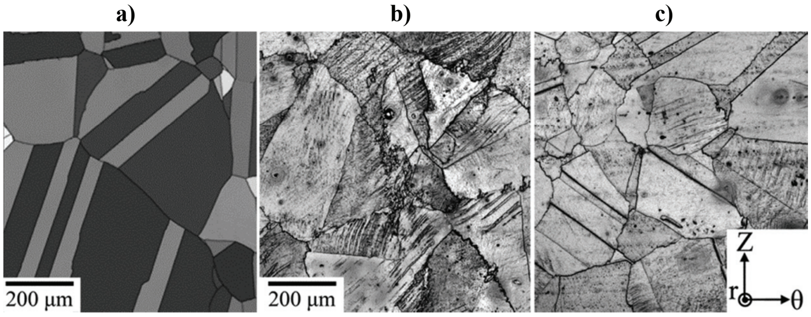

Fig. 1. Electron Backscatter Diffraction (EBSD) map of the initial austenite microstructure; optical microstructures of the deformed samples using deformation route 1 and 2 -b),-c) respectively.

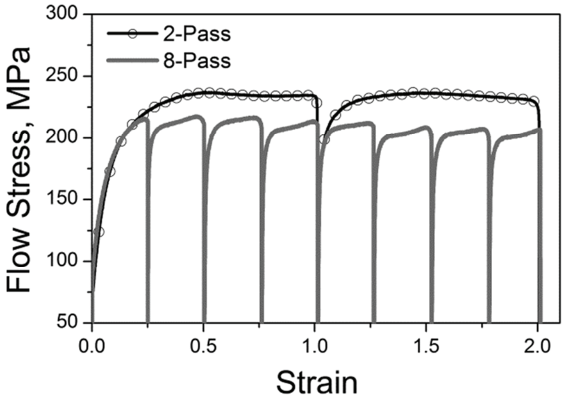

Fig. 2. Flow curves recorded during cyclic torsion deformation of Fe-30wt.%Ni.

The present study confirmed that strain path effect represent one of the most important processing parameters characterising hot metal forming processes. Various austenite state as an effect of different strain path in steel is crucial since it affects the subsequent phase transformations and thus its products what in turn has an effect on the properties of the final materials. Computer modelling of such problems can put some new insight into understanding and optimisation of the processes carried out with strain path changes.

2.2. Accumulative Angular Drawing (AAD) process

In order to carry out the study of the AAD process, a special die was designed such that an ordinary drawing bench could be used (Wielgus et. al., 2010). Microalloyed steel (0.07C/1.37Mn/0.27Si//0.07Nb/0.009N) supplied as a wire rod, with homogenous equiaxed ferrite microstructure and the mean grain size of 15μm, was used in this study. The 6.5mm diameter wire rods were drawn down to the diameter of 4 mm through the set of three dies (in two passes of drawing) with the total strain of 0.97. Although the AAD design allows various combinations of die positioning to be used, the present study was concentrated on the stepped die positioning, in which the offset from the drawing line between the successive dies was equal to 15°.

Optical and electron microscopy observations have shown high level of microstructure inhomogeneity, i.e. substantial grain refinement was achieved in the transverse section of the wires, in the areas near the surface. Grains were also elongated along the wire axis. The dependence of grain shape, size and distribution on the transverse cross section on the processing route is clearly seen in figure3. The refinement of the microstructure is localised in the near-surface layers, however, with various intensities.

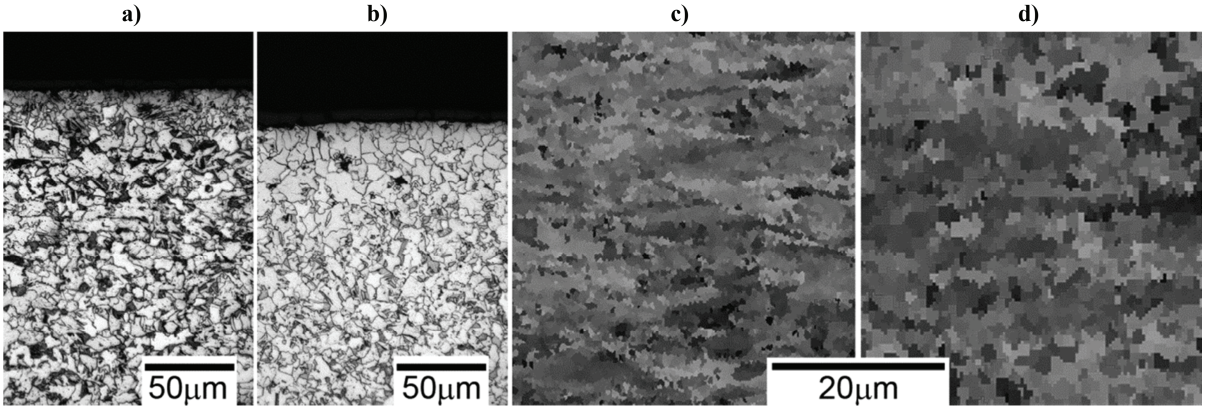

Fig. 3. Initial microstructures of the studied material taken in the longitudinal –a) and transverse –b) cross-section. Euler angle maps of the deformed wires taken near the surface –b) and in the centre –d) of the longitudinal cross section of the deformed wire.

The presented work confirmed that the strain path applied in the AAD process affects directly the microstructure and texture changes in the final product. It is a combined effect of: reduction of the area, strain accumulation in the outer part of the wire due to bending/unbending process, and desired shear deformation. Again numerical modelling can be a valuable support to the experimental research on these effects.

3. NUMERICAL INVESTIGATION

The main aim of the present work was to study whether combination of the multiscale finite element modelling with 3D DMR approach can be used to effectively model complex deformation processes that were described in the previous chapter. Calculations were performed using Abaqus Standard/Explicit package. In both cases, material behaviour was described using elasto-plastic model with combined isotropic-kinematic hardening (Lemaitre & Chaboche, 1990). The evolution law of this model consists of the two main components: a nonlinear kinematic hardening component which describes the translation of the yield surface in stress space through the backstress α:

$$\dot{\alpha}_k = C_k \frac{1}{\sigma^0}(\sigma-\alpha)\dot{\bar{\varepsilon}}^{pl} - \gamma_k \alpha_k \dot{\bar{\varepsilon}}^{pl}, \quad \alpha = \sum_{k=1}^{N}\alpha_k \tag{1}$$

where, α_k is the backstress, N, is the number of backstresses, σ^0 the equivalent stress defining the size of the yield surface and C_k and γ_k are material parameters; and an isotropic hardening component describing the change of the equivalent stress defining the size of the yield surface, as a function of plastic deformation:

$$\sigma_0 = \sigma|_0 + Q_\infty\left(1-e^{-b\dot{\bar{\varepsilon}}}\right) \tag{2}$$

where, σ_0 is the yield stress at zero plastic strain and Q_∞ and b are material parameters. The model is based on the two major model parameters C_k (the initial kinematic hardening moduli) and γ_k (rate at which the kinematic hardening moduli decrease with increasing plastic deformation). These parameters can be specified directly, calibrated based on a half-cycle test data (unidirectional tension or compression), or can be obtained based on the test data from a stabilized cycle (when the strain-stress curve no longer changes shape from one cycle to next).

Parameters of the model have been identified using inverse approach based on data from cyclic torsion test that was performed on studied materials at both deformation temperatures. Example of the comparison of the torque vs. angle data calculated using calibrated hardening model and data measured experimentally (cyclic torsion test) are presented in figure 5. It can be seen that the divergence of the model and experiment is good what proves the accuracy of the applied methodology.

3.1. Multiscale model of the cyclic torsion test

The multiscale model of the torsion test was designed as seen in figure 4. Submodelling technique was used to bridge different scales. Global model of strain gauge was prepared and analysed using Abaqus Standard code. Next, the submodel was generated using the DMR approach and calculations were performed again. A unit cell (100 μm ×100 μm × 100 μm) with 37 grains was created to capture the effect of the process on inhomogeneity of both strain and microstructure. The parameters of the combined material hardening model applied in the submodel were additionally diversified using the Gauss distribution function to reflect differences in the crystallographic orientations.

Equivalent von Mises stress distributions in the global model and in unit cell during the first forward/reverse cycle of torsion test are presented in figure 6a, b. It can be seen that the application of the multiscale modelling approach and its combination with 3D DMR approach resulted in much higher accuracy of the results compared to simulation using only the global model (figure 6a). Global material response obtained from both models can be similar to some extend, however macro scale model neglects inhomogeneities occurring along microstructure features. Additionally 3D DMR properly captured not only inhomogeneites in stress or strain state but also grain shape changes – as an effect of strain reversal (figure 6c). It can be seen that the first pass of cyclic deformation caused grain rotation. Its original position was then restored after strain reversal and application of the second pass of deformation with the same strain level applied in the opposite torsion direction. Macro scale model is unable to provide such detailed results. Due to presented advantages authors decided to apply the same approach to model the AAD process.

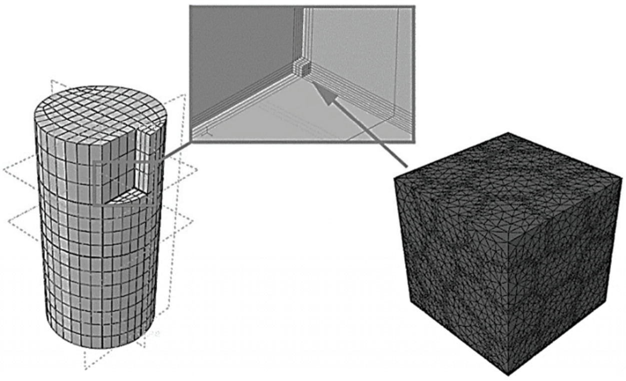

Fig. 4. Multiscale model of the cyclic torsion test.

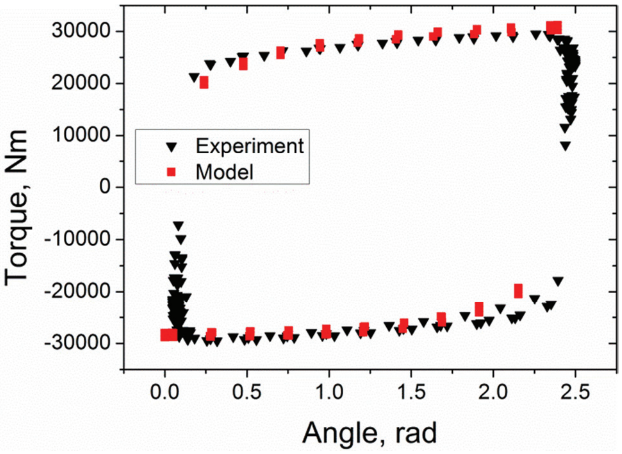

Fig. 5. Comparison of the measured and calculated torque vs. twist angle.

3.1. Multiscale model of the AAD process

Multiscale model of the AAD process due to its complexity requires two steps of submodelling as presented in figure 7. First, global model with 42000 eight-node hexagonal reduced integration elements with hourglass control (C3D8R) was realized using Abaqus Explicit. Drawing of 300 mm long wire with the initial diameter of 6.5mm was modelled. Tools were meshed with quad-dominated discrete rigid elements (R3D). Furthermore, the analysis was replicated on the smaller cylindrical area (10mm long) subdivided from the global model using Abaqus Standard and much finer mesh was used. Finally, second submodel was generated using the 3D DMR approach and calculations were performed again,

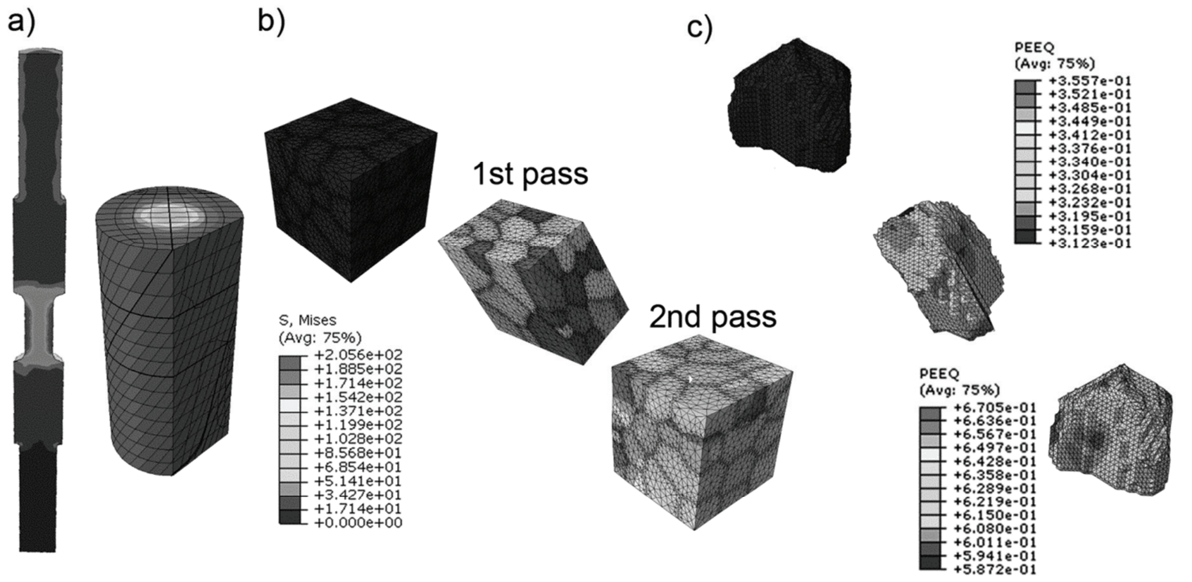

***Fig. 6.** Von Mises stress distributions in global –a) and submodel –b) Equivalent plastic strain distribution in the selected grain –c)*

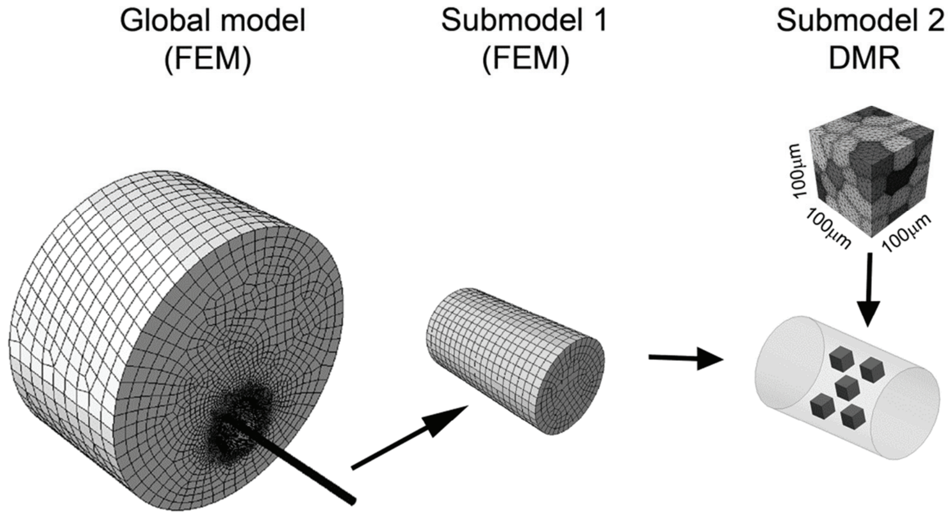

***Fig. 7.** Multiscale model of the AAD process.*

using Abaqus Standard. Set of 5 unit cells (100 µm x100 µm x 100 µm) containing 37 grains each was created to capture the effect of the process on inhomogeneity of both strain and microstructure.

Obtained global equivalent plastic strain distributions on the surface and on the transversal cross section of the drawn wire after the first pass are presented in figure 8.

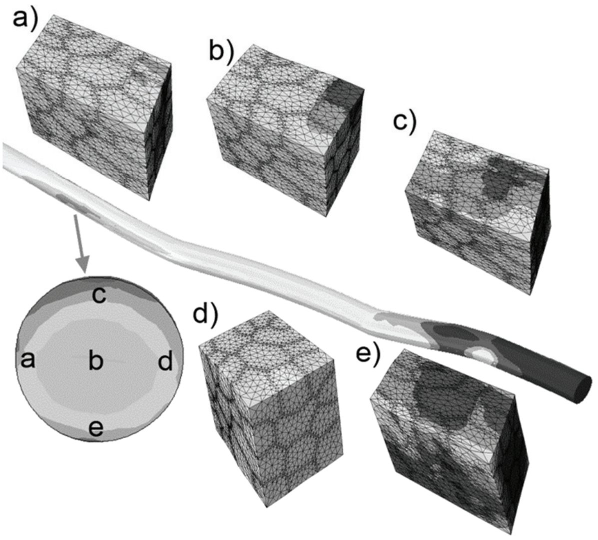

***Fig. 8.** Examples of calculations. Equivalent plastic strain in drawn wire after 1st pass of drawing. Global model and unit cells attached at various positions of the wire's cross-section.*

It can be noticed that the inhomogeneity of strain that is characteristic for this deformation process was properly captured by the applied model. Again, much more detailed information regarding strain localisation and inhomogeneities can be extracted from the submodels in comparison to macro scale model predictions. The 3D DMR approach show different levels of strain inhomogeneity, localisation and distortion across subsequent grains resulting from the AAD process. Higher strain accumulation near the wire surface was also predicted by the computer model (figure 8d, e, f).

It can be seen that application of the 3D DMR approach for the modelling of AAD can be an effective support of the experimental research.

5. CONCLUSIONS

Two complex loading cases with high local strain accumulation were simulated using multiscale FEM model combined with 3D Digital Materials Representation approach. Based on the presented modelling results it can be concluded that the applied modelling strategy was able to catch most of the important phenomena accompanying processes with complex deformation modes with reasonably good accuracy. Future research will focus on application of the crystal plasticity model integrated with DMR what will even more extend predictive capabilities of the proposed methodology.

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ZASTOSOWANIE TRÓJWYMIAROWEJ CYFROWEJ REPREZENTACJI MATERIAŁU DO MODELOWANIA NIEJEDNORODNOŚCI MIKROSTRUKTURY W PROCESACH CHARAKTERYZUJĄCYCH SIĘ ZMIENNĄ DROGĄ ODKSZTAŁCENIA

Streszczenie

W pracy przedstawiono możliwości wykorzystania trójwymiarowej Cyfrowej Reprezentacji Materiału do wieloskalowego modelowania materiałów odkształcanych w warunkach zmiennej drogi odkształcania. W procesach przeróbki plastycznej materiał poddawany jest złożonej historii odkształcania, która charakteryzuje się dużą niejednorodnością odkształcenia. Duży gradient odkształcenia prowadzi z kolei do niejednorodności rozwoju mikrostruktury i powoduje, że przewidywanie własności wyrobu finalnego staje się szczególnie skomplikowane. Odpowiednia kontrola tych parametrów jest utrudniona i może być efektywnie optymalizowana jedynie w przypadku, gdy zostanie wsparta narzędziami numerycznymi. Podejście przedstawione w niniejszej pracy procesu zostało zastosowane do modelowania dwóch procesów przeróbki plastycznej charakteryzujących się zmienną drogą odkształcania: procesu cyklicznego odkształcania na drodze skręcania oraz procesu Kątowego Wielostopniowego Ciągnienia (KWC). W pracy wykazano, że połączenie wieloskalowego modelu MES wraz z trójwymiarową Cyfrową Reprezentacją Materiału wpływa na znaczą poprawę dokładności uzyskiwanych wyników w przypadku modelowania niejednorodności odkształcenia w rozpatrywanych procesach przeróbki plastycznej.

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