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NUMERICAL MODELLING OF INNOVATIVE MANUFACTURING PROCESSES WITH INDUCED STRAIN PATH CHANGES

A review of various bulk metal forming processes that take into account influence of strain path changes on material flow is presented in this paper. Particular attention is put on computer aided design of innovative angular accumulative drawing (AAD) operation. Research in the area of development of metal forming processes taken advantage of strain path phenomena is conducted in many scientific laboratories as the strain patch change effect influences many crucial properties of the deformed material. As a result it provides a possibility of forming materials, which are e.g. difficult to form in a conventional manner. Advantages and limitations of the AAD process are summarized and presented in this work. Difficulties in development of the complex rheological model that takes in to account strain path changes in the deformed material are also presented and discussed.

1. INTRODUCTION

Recent scientific investigations proved close relations between changes in the strain path during deformation and the material structure and formability. Development and changes occurring in the microstructure are identified as one of the main mechanisms that control material flow during deformation path change. It was proven that precise control of the microstructure changes may lead to a reduction in applied loads during these processes. It is also proven that certain deformation conditions (e.g., change of temperature or strain path) may lead to an increase in the forming capabilities of many materials, that are difficult to form by conventional metal forming operations. This statement is supported by research performed in [1], where, material behaviour under two deformation modes was investigated: torsion-torsion-torsion, and torsion-tension-torsion, as presented in Fig. 1a and 1b, respectively. Flow stress obtained from the measurement for the 1st and 3rd step of torsional straining is presented schematically in Fig. 2. Clear drop in the flow curve

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during last deformation is visible in both cases, however it is much more pronounced when straining mode was changed from pure torsion (see: Figure 1a) to torsion-tension-torsion (see: Fig. 1b). These observations confirm a positive effect of the strain path change on materials processing as it results in lower loads needed to deform the material to the same total strain. Similar observations are reported in [2].

The methodology, which involves strain path change during deformation, was already successfully applied to more complex forming operations. Compression with cyclic oscillations is one of the possible examples of a laboratory test that is used to investigate influence of additional oscillations on material behaviour under deformation (Fig. 3). Laboratory equipment for this process was developed at the Department of Process Modelling and Medical Engineering of the Silesian University of Technology in Katowice [3].

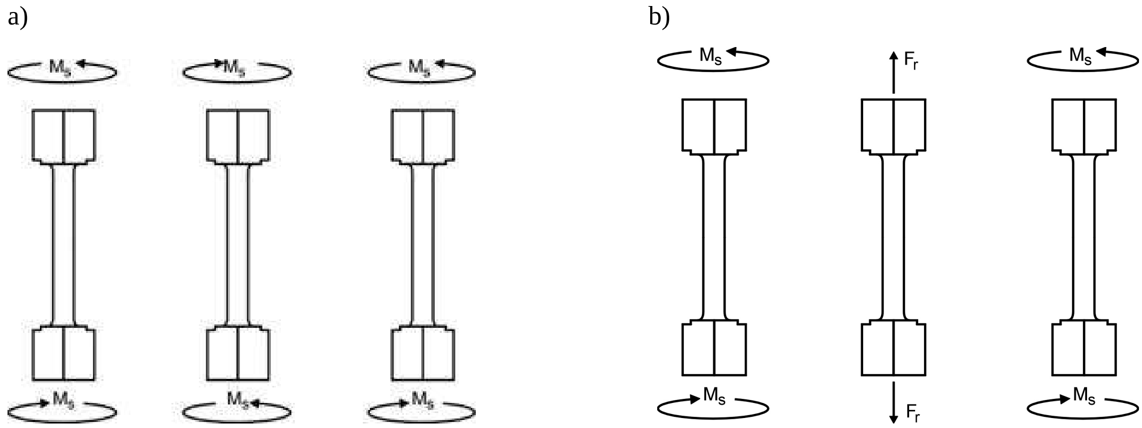

Fig. 1. Schematic illustration of the performed tests with the change in the strain path: a) torsion-torsion-torsion, b) torsion-tension-torsion [1]

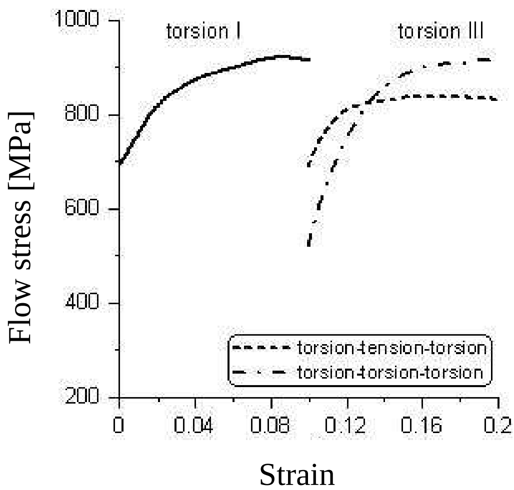

Fig. 2. Comparison of the flow stress recorded during torsional straining for the first and third deformation achieved from torsion–tension–torsion and torsion–torsion–torsion tests [1]

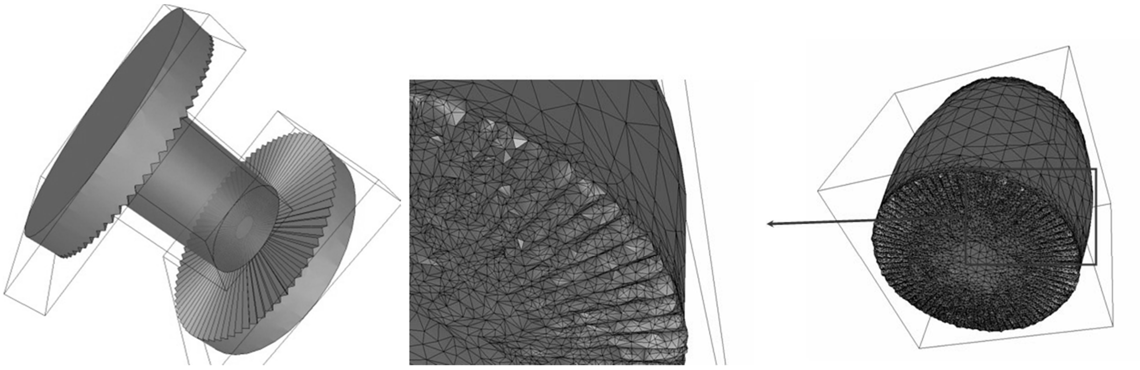

Fig. 3. Schematic illustration of the developed compression test reversible oscillations

This laboratory process is mainly used to analyze differences in material flow, while reversible oscillations are applied and obtained results can be transferred to set up real industrial processes. An example, of such real industrial metal forming operation is the KOBO extrusion. The KOBO extrusion was extensively studied experimentally [4] and numerically [5] and proved its advantages in extruding hardly formable materials. As a result, due to additional reversible die oscillations, large degree of deformation can be obtained without danger of material failure. The idea of the process is presented in Fig. 4.

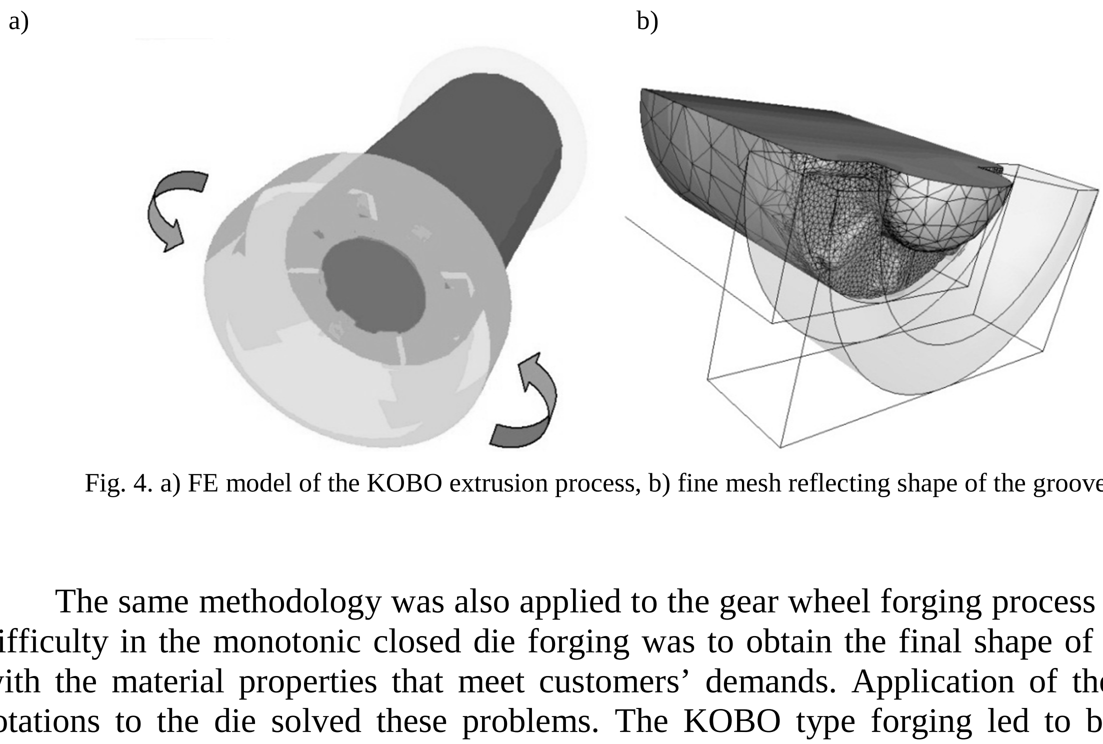

Fig. 4. a) FE model of the KOBO extrusion process, b) fine mesh reflecting shape of the grooved die

The same methodology was also applied to the gear wheel forging process as the main difficulty in the monotonic closed die forging was to obtain the final shape of the product with the material properties that meet customers' demands. Application of the reversible rotations to the die solved these problems. The KOBO type forging led to better filling of the groove and allowed to obtain final product with higher accuracy in shape in comparison to monotonic forging. Additionally, it led to a decrease in die wear due to reduction in applied loads. Research on this matter can be found in another authors work [6]. Example of the process and obtained shape of the product are presented in Fig. 5.

As presented, all those examples of processes take advantage of the strain path change effects and are focused on a bulk forming operations.

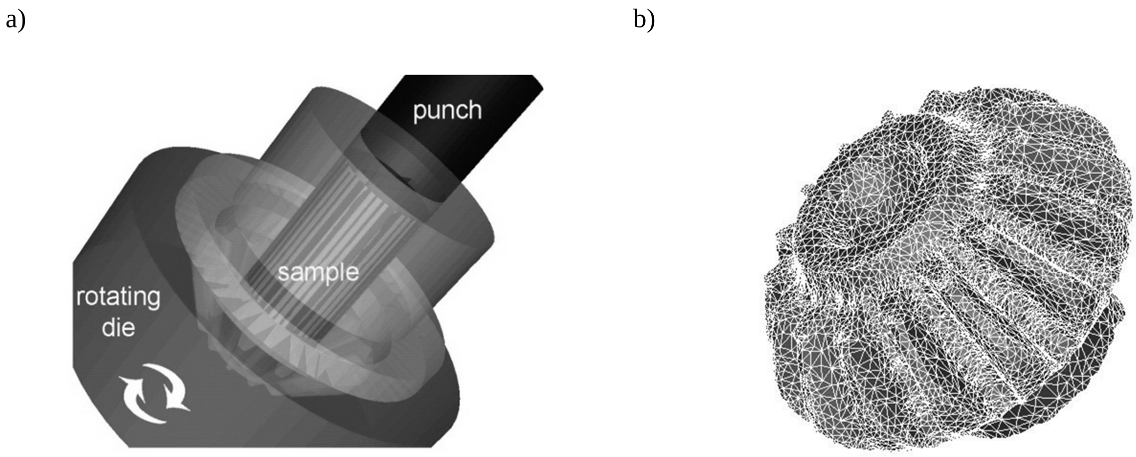

Fig. 5. a) FE model for gear wheel forging with reversible die oscillation, b) FE mesh after deformations

In the present work, the recently developed in the Department of Metal Forming at AGH University of Science and Technology in Krakow, Accumulative Angular Drawing process (AAD) [7],[8] is presented and discussed with respect to its potential to produce wires with enhanced properties thanks to controlled strain accumulation that leads to local high grain refinement. In this process, that is schematically presented in Fig. 6, a complex strain path can be applied, and large strain accumulation is introduced to refine the microstructure of a drawn wire.

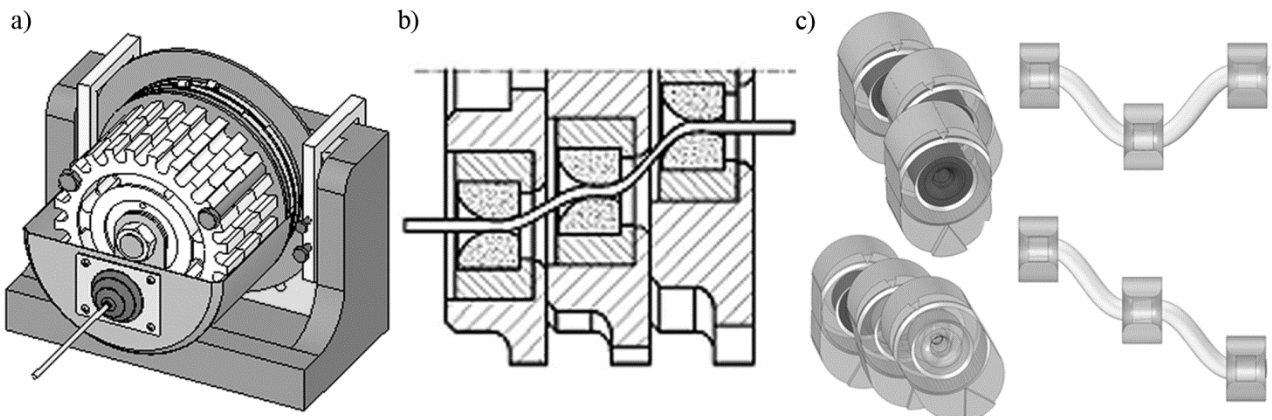

Fig. 6. Scheme of the AAD process: a) top view, b) section view, c) alternate and stepped dies' assembly settings

The applicability of strain path change in the AAD process allows for the preferred distribution of effective strain in the entire cross-section of the drawn product, which, in turn, introduces microstructure inhomogeneity at the cross-section of the wire. These effects

– if properly controlled – enable the achievement of a desirable combination of mechanical properties in the final product. In the present study, analysis of microstructure development and its inhomogeneity was carried out in order to understand the deformation mechanisms and to establish the correlation between deformation, microstructure and mechanical properties observed in microalloyed steel. In order to optimise the process and to learn how to control the level of strain inhomogeneity, robust multiscale computer model was developed. It has already been proven that by the aid of numerical tools it is possible to predict strain inhomogeneity levels in the AAD products, and thus, properly control the process parameters. This in turn enables to introduce controlled inhomogeneneity of strain and, by accumulation of deformation energy, to induce grain refinement across the cross-section of the wire. As a result, enhanced properties compared to conventional wire drawing processes can be obtained.

2. ACCUMULATIVE ANGULAR DRAWING PROCESS

The AAD process (Fig. 6), thanks to its design, induces high strain accumulation in the surface layers of the processed wire, which allows to achieve increased mechanical properties and ductility in wires characterised by small diameters. In the present study, wires made from a fully recrystallized microalloyed steel (0.07C/1.37Mn/ 0.27Si//0.07Nb/0.009N) were investigated. Wire rods with diameters of 6.5 mm and average grain size of 15µm were drawn to wires of 4.0mm diameter by applying steeped dies positioning and according to the drawing schedule that is presented in Fig. 7. Although three different positioning of the dies are possible (linear, stepped and alternate), the present study was focused on the stepped dies' positioning, as it was found to give the best combination of the strength and ductility in the final product [8].

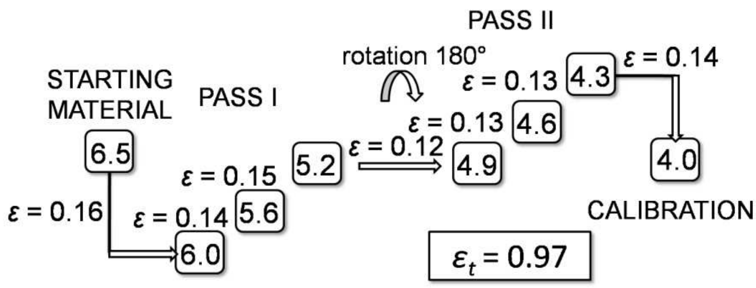

Fig. 7. Scheme of the AAD process. The two-pass schedule

Drawing was carried out at slow speed (0.05m/s) to eliminate the effect of the heat generated by cold working. The reduction of cross section area, the strain induced in the outer part of the wires, due to bending/unbending processes and the desired shear deformation were the main sources of strain accumulation in the final product of the AAD process. The cold drawn wires, after deformation, were annealed for 1200s at different temperatures (500 ÷ 700°C) and then subjected to microstructure analysis and mechanical testing. Examples of optical micrographs taken at various positions of the transverse cross section of the drawn and annealed wire are presented in Fig. 8. Microscopic observations have revealed significant grain refinement in the regions near the wire surface, with various intensities. Different levels of microstructure inhomogeneity not only at various positions of the wire cross section but also along its axis (Fig. 8 a and b) result from complex deformation modes (area reduction, shear and burnishing), however, their quantitative assessment requires further analysis.

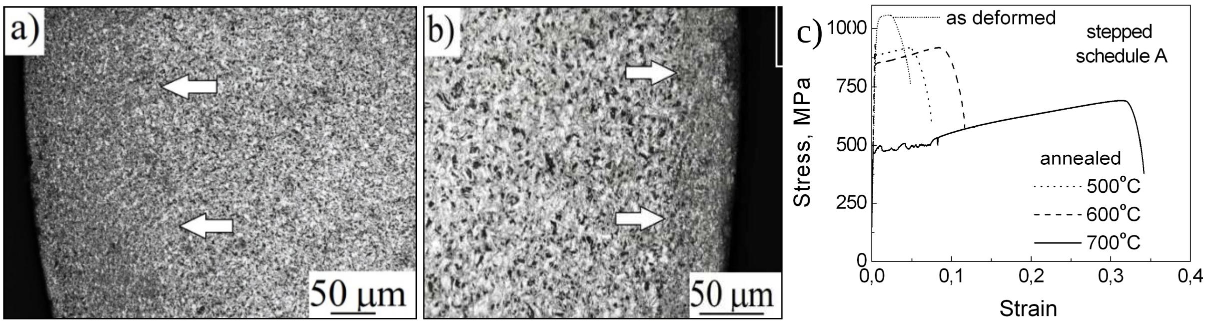

Fig. 8. a-b) Examples of inhomogeneous microstructures observed on the transverse cross section of the wires drawn with the stepped die positioning, and annealed at 500ºC, c) effect of the post deformation annealing temperature on the properties of the drawn wires

Presented in Fig. 8c flow curves recorded during tensile test performed on the drawn and annealed wires, show that post-deformation annealing plays a crucial role in shaping strength-to-ductility ratio. The higher annealing temperature the more ductile wires are. At this initial point of the study, it can be stated that processing by the AAD plays a dual role in these microalloyed steel wires by both refining the microstructure and significantly altering the strength/ductility ratio. It can be argued that the complex path and resulting inhomogeneity of deformation of the as-AAD samples could be a source of an increase in the ductility, which was also observed previously [9]. To extend this study, an efficient numerical multiscale model can be created.

3. MULTISCALE MODELLING OF THE AAD PROCESS

The main aim of the present work was to build a robust computer model of the AAD process. The emphasis was put on the proper representation of the evolution process of strain inhomogeneity what in the future will enable to optimise it towards its better control and improvement of the properties of wires. The major emphasis in the developed model was put on the proper representation of the evolution of strain inhomogeneity in order to control and improve the properties of produced wires. In the present study, due to the complexity of the AAD process, a concurrent multiscale approach based on two steps of submodelling was proposed (Fig. 9). The first step of submodelling was applied to solve a problem with one mesh describing the global domain. Then another and generally finer mesh was used to reanalyse a certain subpart of the global domain which is of particular interest. To perform such analysis, either the displacement field or the stress field from a global domain has to be interpolated to the cutting boundary of a submodel having fine mesh along the edges. The main advantage of such approach is that very detailed information can be derived from small area of the global domain with no need to perform costly numerical analysis with very fine mesh in the whole model. First, a global model with 42,000 eight-node hexagonal reduced integration elements with hourglass control (C3D8R) was run using Abaqus Explicit – Fig. 9a. Drawing of 300mm long wire with an initial diameter of 6.5mm was simulated. After that, the displacements of the nodes corresponding to face and edges of the cylinder (submodel 1) were read and used as boundary conditions for the second submodel. Then, the analysis was repeated on this smaller cylindrical area (10mm long) extracted from the global model using Abaqus Standard, and a much finer mesh was used – Fig. 9b.

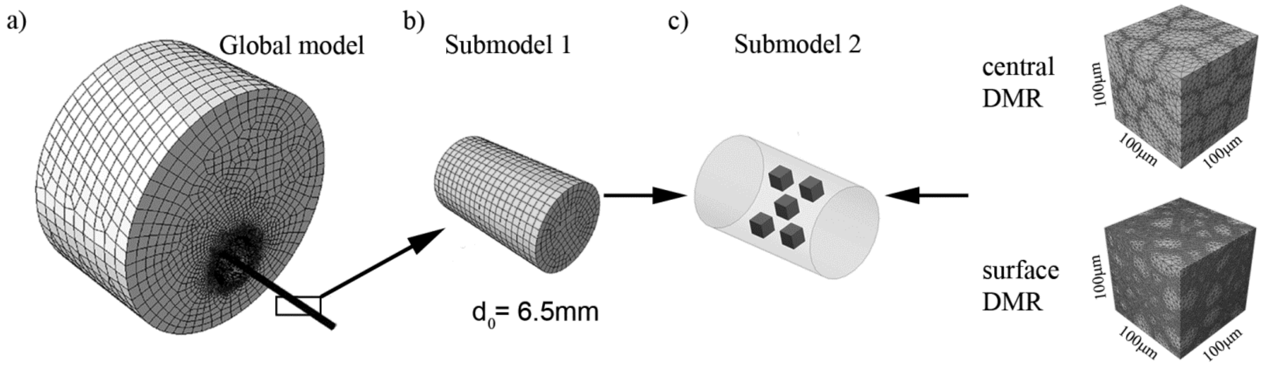

Fig. 9. Multiscale model setup of the AAD process

Finally, a second submodel was generated using the Digital Materials Representation approach (DMR) [10],[11],[12], and calculations were performed again using Abaqus Standard – Fig. 9c. A set of 5 unit cells ($100\mu m^3$) was created in order to capture the effect of the process on strain inhomogeneity. In order to take into account the microstructure inhomogeneity across the wire cross section, central DMR was created with 37 grains whereas all the near-surface DMRs represented unit cells with 100 grains. The material model used in the present work was the combined kinematic-isotropic Chaboche model [13]. The evolution law of the model consists of the two main components: a non-linear kinematic hardening component, which describes the translation of the yield surface in the stress space through the back stress α, 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. The model parameters were identified using an inverse analysis [14] based on the data from a cyclic forward/reverse torsion test [15]. It has already been proven that the application of the inverse approach resulted in a significant improvement of the accuracy of the results, compared to the simple isotropic model that is commonly used in the literature [16] especially in the case of the simulation of the processes that are characterised by strain path changes.

4. RESULTS

As mentioned, the multiscale model was built to simulate the AAD process in order to verify the effect of strain path change on both strain and microstructure inhomogeneity of drawn wires. An example of Mises stress distributions in the global model and at two key positions of the transversal cross section of the drawn wire after the first pass of drawing through the 3rd die is presented in Fig. 10. It can be seen, that thanks to the application of the multiscale approach, much more details concerning stress distribution at various positions of the drawn wire can be obtained. This approach seems to be very promising, as representation of the microstuctural features at various scales, offers much more physically-based numerical tool for the simulation of the processes characterised by a complex strain path history. Comparing numerical results with the experimentally obtained microstructures it can be concluded that the inhomogeneity of stress that is characteristic for this deformation process was properly captured and predicted by the proposed model.

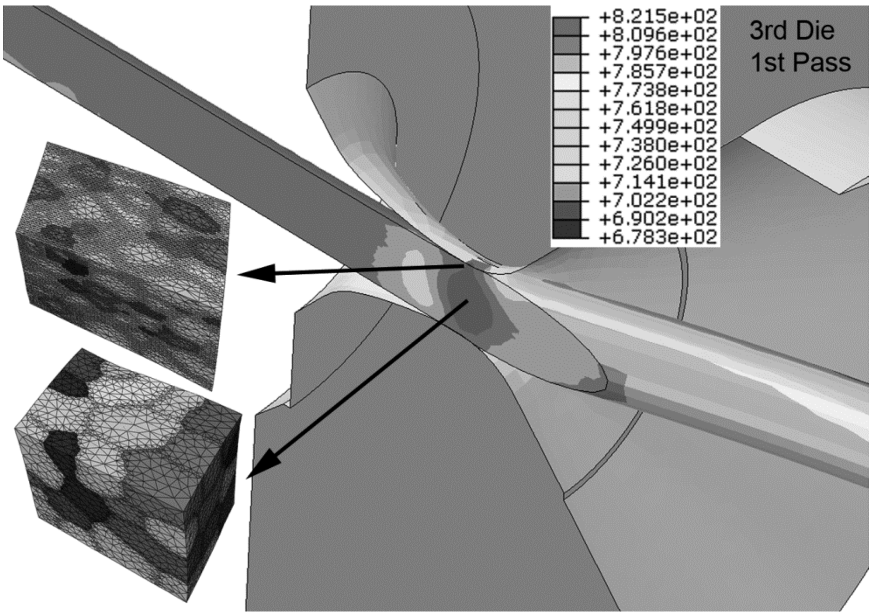

Fig. 10. Equivalent Mises stress distributions in the global model and DMR calculated near the top surface and centre of the cross section of the wire after 1st pass of drawing in the 3rd die

Figure 11 shows example of numerical results where equivalent plastic strain distribution was calculated in the global model and in the submodels. It can be seen that the equivalent plastic strain is localised close to the surface of the wire. Much more detailed information regarding strain localisation and inhomogeneity can be extracted from the DMR approach, compared to the global model. Unit cells simulated using the DMR approach show different levels of strain inhomogeneity, localisation and distortion resulting from the AAD process.

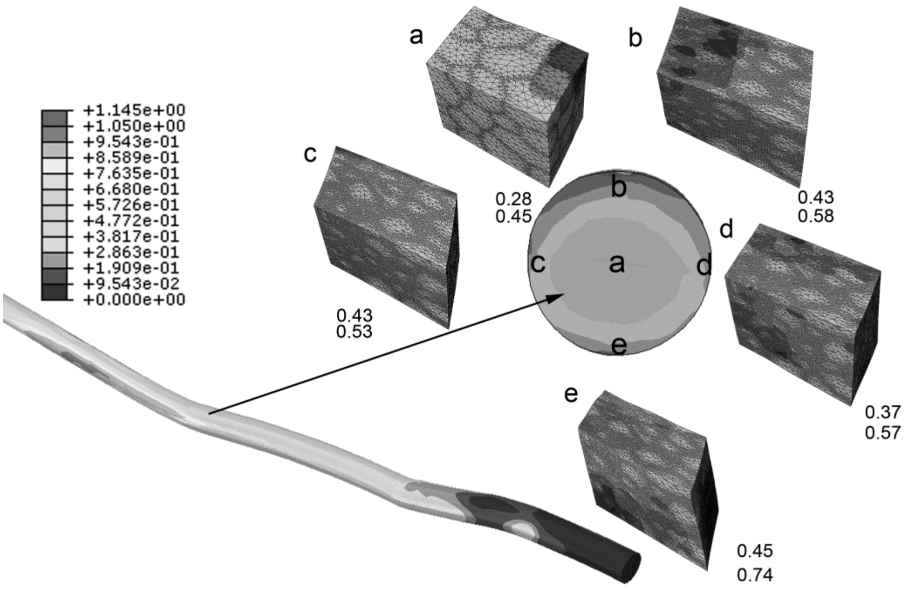

Fig. 11. Equivalent plastic strain distributions calculated in the global and local models

Using the DMR approach it is also possible to capture higher grain refinement near the surface, which is a result of higher strain accumulation, (Fig. 11b, e). The presented results show the potential of the proposed strategy; however, more detailed quantitative analysis requires further work and more experimental data.

5. CONCLUSIONS

In the present paper, review of various bulk metal forming processes that take advantage of the strain path changes was presented. Special focus was put on recently developed Accumulative Angular Drawing process. Based upon results from the presented research the following major conclusions can be drawn:

1. Application of the AAD process allows control of inhomogeneity of both deformation and microstructure in the drawn wires. As a result, it is possible to shape the mechanical properties of the final products and obtain wires with better combination of strength and ductility compared to typical wire drawing processes.
2. With a more complex strain path and more energy accumulated in the wires during the AAD process one should expect stronger microstructural effects and mechanical property changes in the drawn wires compared to traditional wire drawing process.

3. Proper choice of the rheological model that takes into consideration strain path changes and its application to the multiscale analysis is crucial in order to effectively model the complex strain path processes and to control strain and microstructure evolution, and thus, to optimise the properties of the final products.

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