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NUMERICAL ANALYSIS OF DATA TRANSFER QUALITY IN THE 3D MULTI-SCALE UNCOUPLED CONCURRENT MODEL CONNECTED WITH DMR

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Abstract

Analysis of the quality of obtained results from a 3D multiscale concurrent finite element numerical model based on Digital Material Representation (DMR) concept is the main aim of the research. Particular attention is put on an influence of different number of data transfer nodes between subsequent scales on material behavior predicted by a micro DMR model. Conclusions are drawn based on results in the form of equivalent strain distribution, homogenized stress-strain curves and samples shape changes.

Key words: multiscale model, digital material representation, finite element method

1. INTRODUCTION

Light and durable integral constructions are now in high request, for e.g. automotive or aerospace industries, as they enable reduction in CO_2 emission due to cars and planes smaller fuel consumption. Integral elements are made from one piece of material so they do not need any montage operations, what is also an advantage from natural environment protection point of view i.e. because of energy consumption reduction. What is more, production of so called integral parts can be faster and less expensive, than conventional joining of many smaller elements into a single complex construction. Thus, in recent years different manufacturing technologies dedicated to light and durable integral elements made from one piece of metal were investigated e.g. machining, rolling, casting or forging, etc. (Wiślicki, 1964). Unfortunately, most of proposed solutions are very expensive or connected to some technical problems. Therefore, forging seems to be the best way of obtaining integral elements because of the high quality of the final product. Unfortunately, integral elements that can be used in aerospace or automotive industries, are characterized by small thicknesses, wide surfaces and stiffening ribs, which are problematic to form, from forging point of view. Obtaining such complex and thin parts during forging process requires immense press loads, impossible to get on conventional, easily available presses.

Thus, a new solution, based on modified forging process dedicated for elements especially useful in the aerospace industry, was proposed in (Grosman et al., 2012a; Grosman et al., 2012b; Grosman et al., 2006). This innovative process of obtaining light and durable integral elements, answers problems presented above and joins the advantages of forging and incremental forming (IF) idea. IF concept enables obtaining large deformations by adding many smaller deformations. That way, IF gives a possibility to form elements on easily available presses even with small loads capacities and is a good solution to form materials considered as hardy deformable. The concept of proposed process is based on division of

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a single press die into a series of smaller anvils that are grouped into series of sets. The distance between sets of anvils is strictly connected with expected stiffening rib dimensions. The anvils are pressed into the material due to the movement of additional die in the form of roll (figure 1).

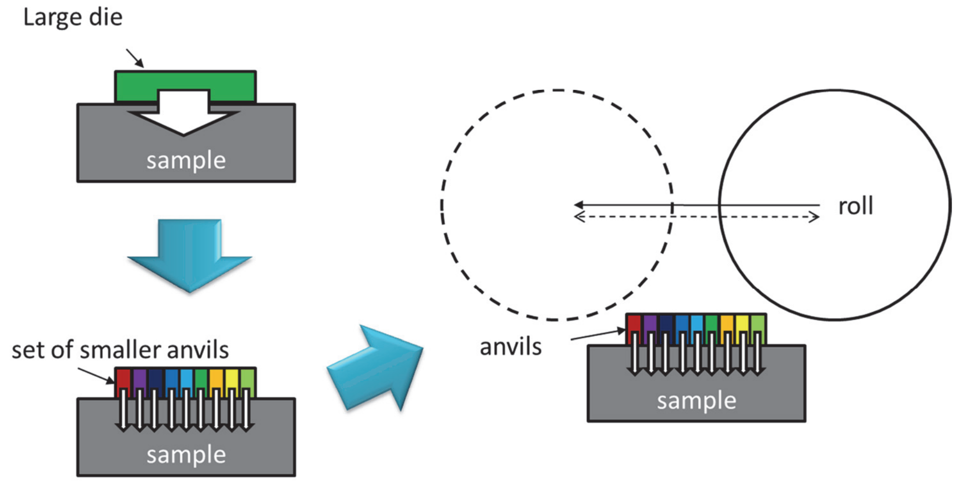

Fig. 1. *Illustration of novel incremental forming (IF) process.*

However, to successfully apply this innovative technology at the industrial scale, engineers have to gain detailed knowledge on mechanisms that control deformation and microstructure evolution during complex forming conditions occurring in the incremental process.

Unfortunately, experimental research is expensive and time consuming, especially when material behavior at the microstructure scale is investigated. However, thanks to the continuous and dynamic technological progress, especially in the information technology (IT) field, there are many possibilities of efficient numerical support of experimental research works. One option is to use an advanced computer modelling techniques, which give a possibility to obtain fully virtual process that joins the digital material, simulation of deformation conditions and computer analysis of obtained results. This leads to the cost reduction of laboratory research, facilitates the new materials design and also enables an analysis of materials behavior under manufacturing and exploitation conditions.

Thus, authors decided to support experimental investigation on the IF process by advanced numerical simulations. To make a detailed analysis of material flow at different levels, not only at the macro scale but also deeper, at the micro scale level, a concurrent multiscale numerical model supported by the Digital Material Representation (DMR) concept was developed.

However, when multiscale solutions are investigated the key aspect that have to be addressed is proper data transfer between length scales. Thus, the work addresses the issue of data transfer quality in the developed multiscale concurrent model for IF process simulations.

2. MULTISCALE MODEL OF THE IF PROCESS

Multiscale numerical models enable detailed analysis of material flow during simulation, not only and the macro level, but also at the level of subsequent grains of the investigated material structure. The first step of multiscale model development is preparation of the macro scale model that in the paper corresponds to the investigated IF process (figure 2). The moving rolls, lower die, two sets of 6 anvils each, sample with material data and boundary conditions have been defined during development of the 3D macro scale model (Szyndler et. al., 2016). The classical Hensel-Spittle material flow stress model with constants established by the inverse analysis (Szeliga et. al., 2006; Kusiak et al., 2012) was used to generate material data of the commercially pure aluminum:

$$\sigma_p = Ae^{m_1 T} T^{m_9} \varepsilon^{m_2} e^{m_4/\varepsilon} (1+\varepsilon)^{m_5 T} e^{m_7 \varepsilon} \dot{\varepsilon}^{m_3} \dot{\varepsilon}^{m_8 T} \quad (1)$$

where: σ – flow stress; ε – equivalent strain; $\dot{\varepsilon}$ – equivalent strain rate; T - temperature in ˚C; model coefficients: A = 139.0000011, m_1 = -0.00184706, m_2 = 0.0623991, m_3 = 0.009336435, m_4 = -1.76441E-05, m_5 = -0.001861512, m_7 = 0.063127492, m_8 = 7.17027E-05, m_9 = 0.038132999.

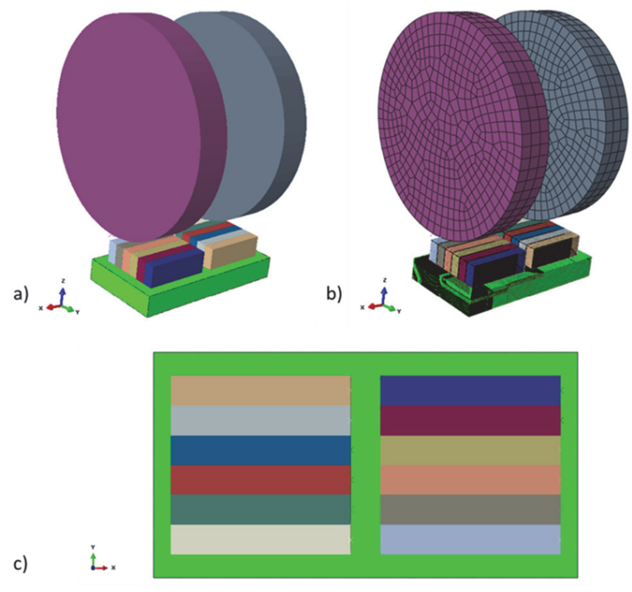

Fig. 2. Macro-scale model of developed IF process a) without FE mesh, b) with FE mesh, c) top view on sample and anvils without visible rolls.

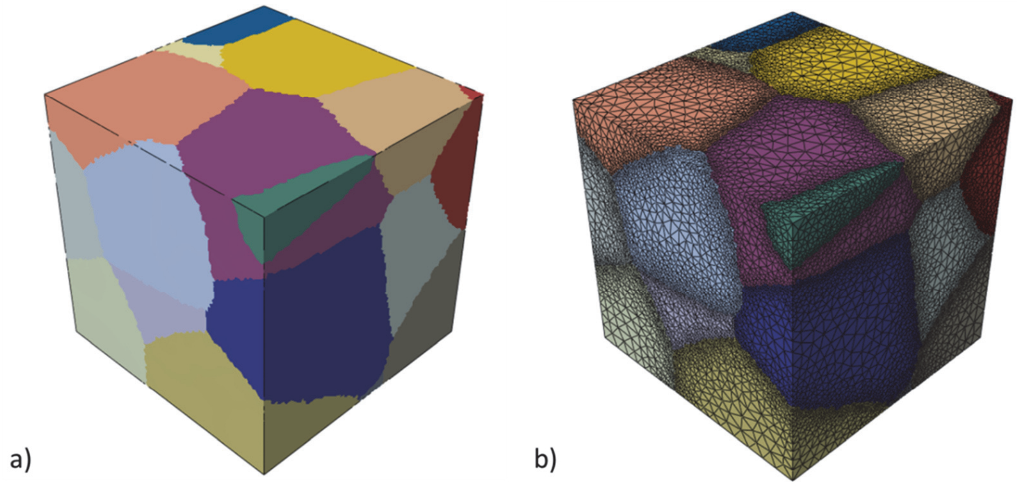

Fig. 3. DMR morphology a) without the FE mesh, b) with the FE mesh.

To precisely describe material morphology, the micro scale digital material representation model was developed based on the methodology described in (Szyndler et al., 2013; Szyndler & Madej, 2014). The DMR model contains 20 grains as presented in figure 3. During the investigation a tetrahedral FE mesh (element type: C3D4 – 4-node linear tetrahedron) additionally refined along the grain boundaries was used (figure 3b). Each grain is described by slightly different flow stress curve to make an impression of different crystallographic orientation. Two extreme hardening behaviors were identified during channel die compression of Al mono-crystals in hard and cube orientations, respectively. Other generated flow stress curves are between the lower and upper range of the identified extreme conditions and set to subsequent grains in the developed DMR model. Proposed micro DMR model with material morphology, FE mesh and material data was then located in the interesting region of the macro scale and the concurrent multi scale IF model was eventually established. That way not only macro scale but also micro scale material behavior can be investigated during the IF process.

Data from the macroscale model are transferred into the micro scale by series of FE nodes located at the boundaries of these models, respectively. Therefore, the key aspect in this approach is to ensure that an appropriate partitioning strategy is used in the macro model for extracting the steady state boundary conditions to be imposed at the micro scale model. Data are transferred to the micro scale nodes from macroscale ones by an interpolation method within the exterior tolerance zone. As can be expected, the quality of obtained results depends on number of transfer nodes at the macro scale level, as coarse mesh is usually used to decrease the computational cost (Szyndler et al., 2013). Thus, it is important to prepare a macro model of the IF process that ensures that results at the micro scale level are not affected by the interpolation. So far such problem was addressed only in the 2D space, see e.g. (Szyndler et al., 2013).

To investigate mentioned issue in 3D space, the concurrent multiscale model was developed (figure 4), with different number of data transfer nodes on a single wall at the macroscale, namely 9, 25, 81, 121, 256 and 441 nodes (figure 5). The amount of boundary nodes at the micro scale model wall is constant and approx. equal to 1700. Numerical simulations with specified deformation conditions were carried out in the commercial finite element program

Abaqus. The Digital Material Representation model of the aluminum sample 435.6×435.6×435.6 μm was attached to the macro scale sample (75×40×10 mm) in the area located underneath two anvils as seen in figure 4.

Based on presented results it can be stated that repetitive DMR model behavior starts with 256 macro FE mesh data transfer nodes on each wall. Also after the analysis of samples shapes obtained from the DMR simulation the same assumption can be made. Of course the higher the mesh density is at the macro scale level, the more accurate results from the DMR model are expected. However, after the identified threshold this increase in accuracy does not really seem to compensate significant increase in computational time.

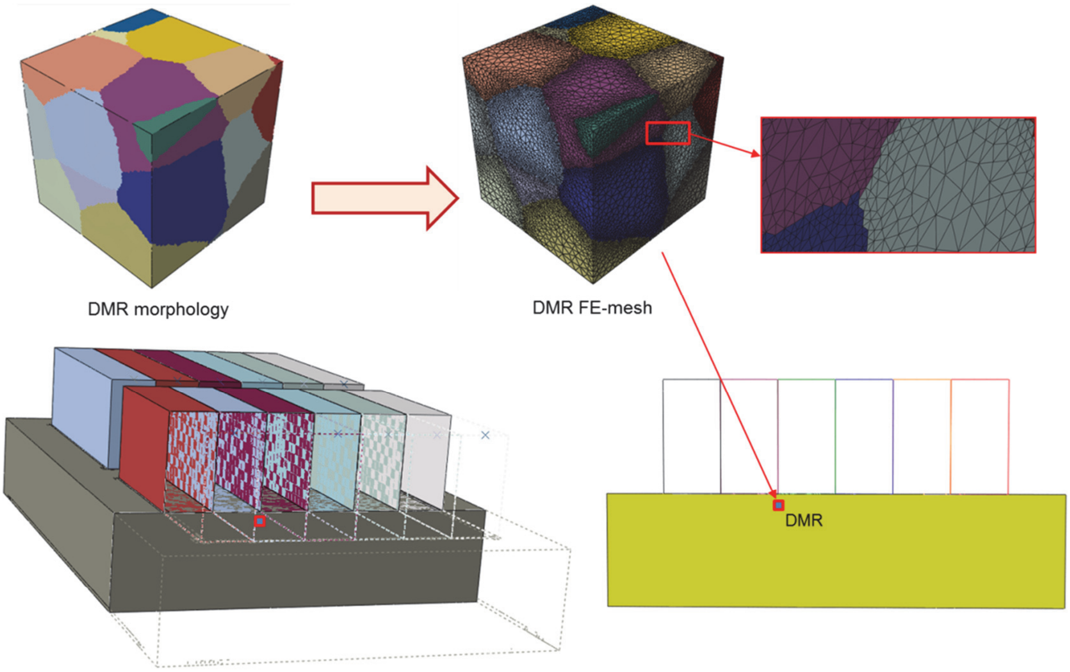

Fig. 4. *Concept of developed multiscale model of the incremental forming process.*

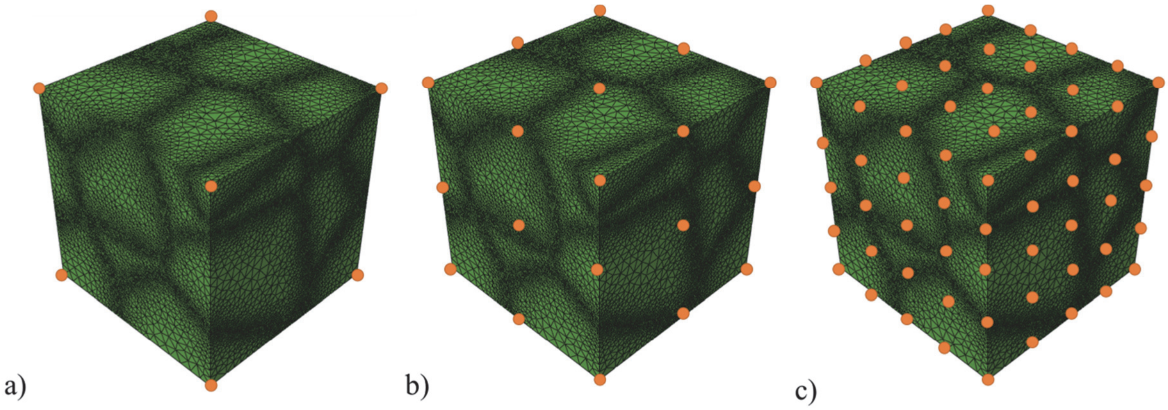

Fig. 5. *Schematic view on different data transfer nodes between scales: a) 4, b) 9, c) 25 nodes on each wall.*

Simulation of four roll passes at the macro scale was computed with the roll frequency equal to 0.5 Hz and 0.2 mm indentation depth per a single roll pass. Results in the form of equivalent strain distributions, micro models shape and homogenized flow curves after the IF process are presented in figures 6-9, respectively.

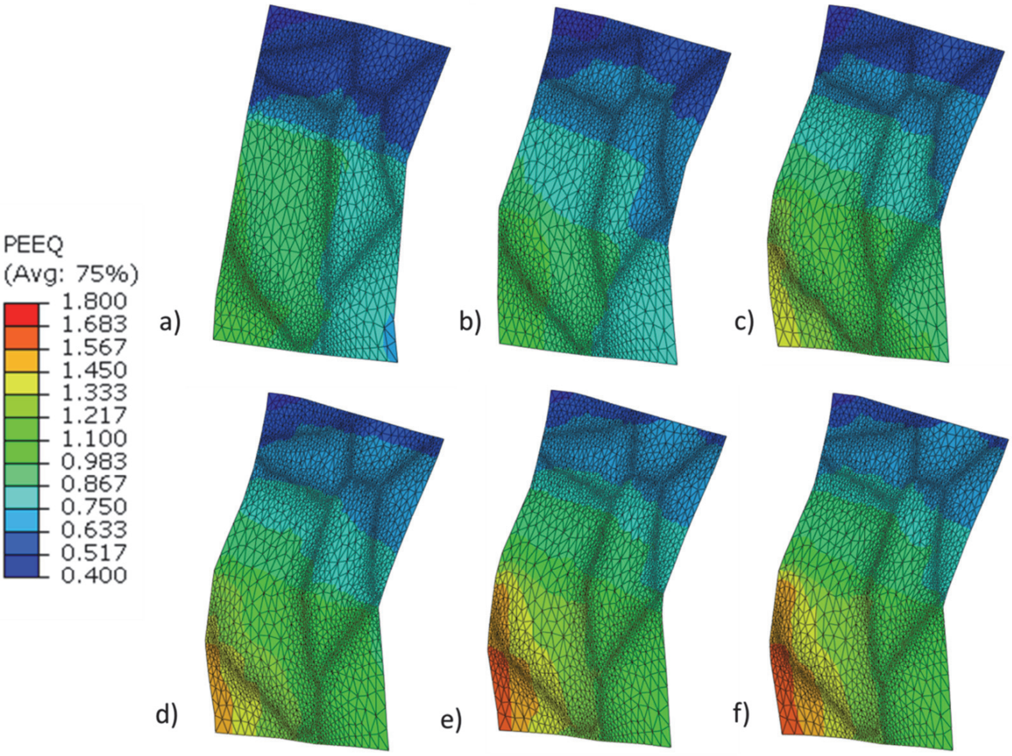

***Fig. 6.** Equivalent strain distribution in DMR model with a) 9, b) 25, c) 81, d) 121, e) 256, f) 441 data transfer nodes on each wall.*

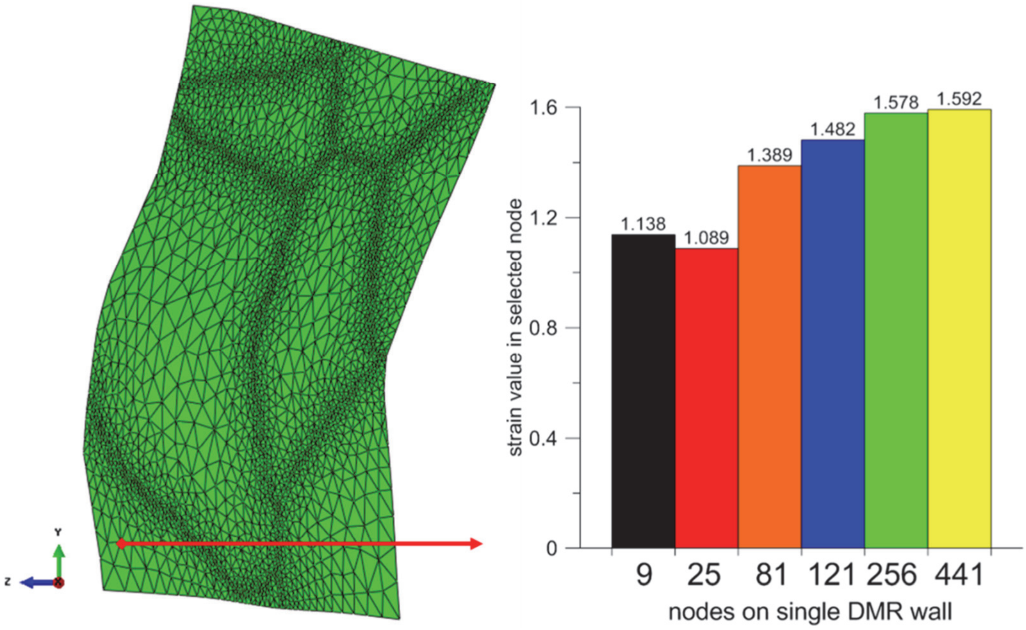

***Fig. 7.** Equivalent strain value in the selected node after the IF process.*

3. CONCLUSIONS

The aim of the paper was a determination of a minimum number of data transfer nodes between macro model and micro DMR solution in a multiscale numerical simulation of a novel incremental forming process. Six different densities of mesh at the macro scale were used during the investigation. Obtained results allow to conclude that for investigated cases the minimum number of transfer nodes, that does not significantly affect quality of obtained DMR behavior, is 256 on each wall. Higher number of nodes slightly improve the predictions, however the computational time drastically increases.

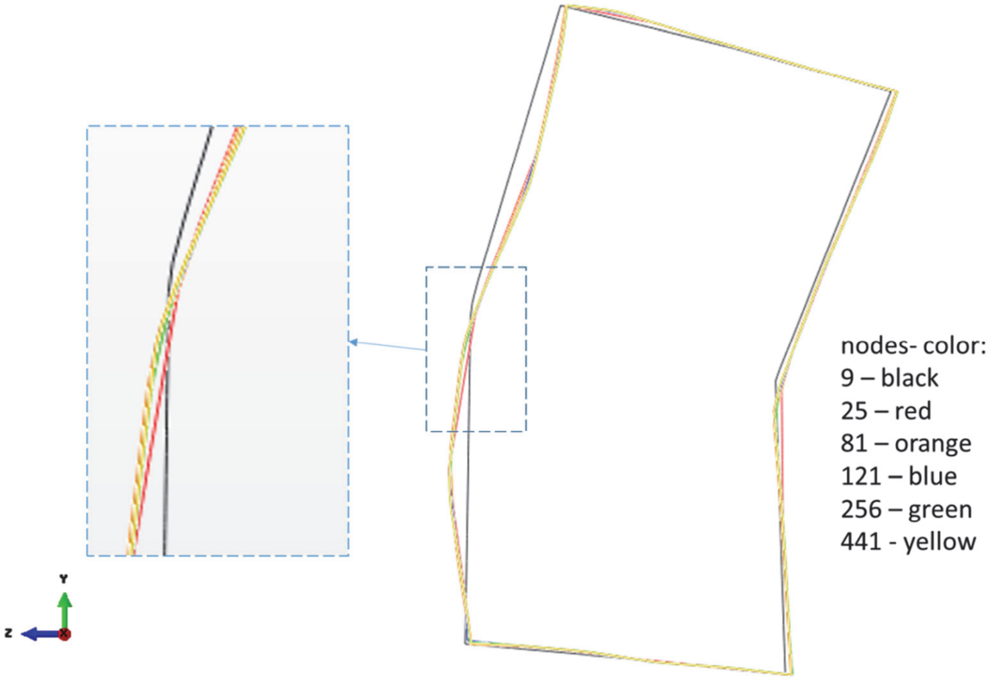

Fig. 8. *Shapes of the DMR model after the IF process for different number of data transfer nodes.*

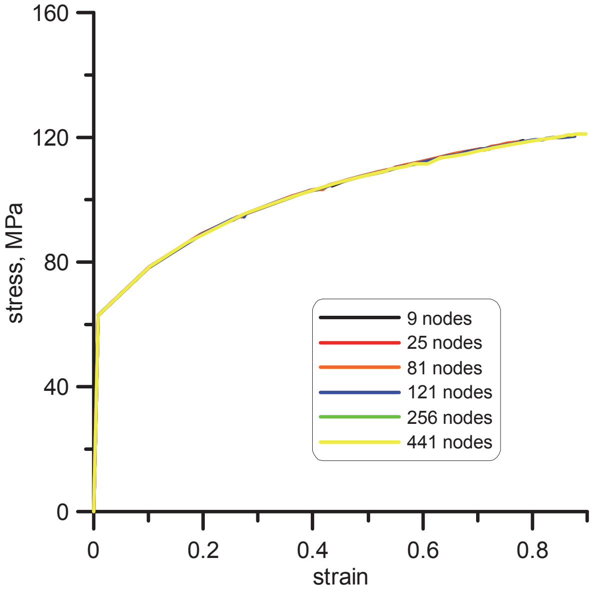

Fig. 9. *Homogenized stress/strain curves after the IF process in the DMR model.*

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ANALIZA NUMERYCZNA WPŁYWU ILOŚCI WĘZŁÓW SIATKI MES NA JAKOŚĆ WYNIKÓW W MODELU DMR PODCZAS TRÓJWYMIAROWEJ WIELOSKALOWEJ SYMULACJI

Streszczenie

Celem pracy jest analiza jakości uzyskanych wyników podczas stosowania współbieżnego trójwymiarowego modelu wieloskalowego, bazującego na kombinacji modeli elementów skończonych w skali makro i mikro. Szczególną uwagę poświęcono wpływowi zróżnicowanej ilości węzłów przekazujących dane między skalami mikro i makro na zachowanie się materiału w skali mikro. Wyniki przedstawiono w formie rozkładu odkształceń, krzywej płynięcia materiału i zmian w kształtach próbek w skali mikro.

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