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Joanna SZYNDLER<sup>1\*</sup> Konrad PERZYNSKI<sup>1</sup> Lukasz MADEJ<sup>1</sup>

# MODELLING OF MATERIAL FLOW DURING INCREMENTAL FORMING PROCESS ON THE BASIS OF DIGITAL MATERIAL REPRESENTATION CONCEPT

The main goal of the work is development of the multiscale numerical model of the incremental forming process for manufacturing integral elements applicable in the aerospace industry. Description of the proposed incremental forming concept based on division of large die into a series of small anvils pressed into the material by a moving roll is presented. A complex multi scale numerical model of mentioned incremental forging process based on the digital material representation (DMR) concept was developed and is also described within the paper. Finally, obtained results in the form of strain distribution are presented and compared with the outcome from conventional forging at the macro and micro scale, respectively.

## 1. INTRODUCTION

Reduction in the overall mass of the transportation vehicles e.g. aircrafts, is a driving force for fast development of new materials as well as manufacturing technologies that can provide lighter components. Reduction in weight of the commonly used constructional elements gives a possibility to reduce the amount of consumed fuel, what minimizes exploitation costs and additionally can reduce the amount of carbon dioxide emission into the atmosphere, what is important from the environmental protection point of view. One of the options for a successive decrease of aircrafts weight is application of integral parts made from light alloys, i.e. aluminum, titanium or magnesium. Integral elements are made from one block of material, instead of many smaller parts that used to be joined together [1]. Avoidance of joints (e.g. welds, rivets), causes that the product is lighter, more durable and less susceptible for cracking in vital locations during exploitation. Integral part concept is presented in Fig. 1. Application of integral elements in the aerospace industry also enables reduction of exploitation costs of other airplane components (e.g. tires), what extends their lifespan and lowers conservation costs and production outlay even up to 40% [1].

<sup>&</sup>lt;sup>1</sup> AGH University of Science and Technology, Cracow, Poland

<sup>\*</sup> E-mail: joanna.szyndler@agh.edu.pl

Unfortunately, because of complicated shapes and large area sizes, forming such components with traditional forging methods is practically impossible [1]. That is why, to obtain integral parts, a series of manufacturing technologies based primarily on machining, rolling, extrusion or casting were developed [1]. Recently, rapid manufacturing by 3D printing is becoming more and more popular [2]. Regrettably, most of these technologies are connected with substantial costs and technical problems, small efficiency, limited applications or significant waste of material.



Fig. 1. Example of a part made from a) several smaller elements in a conventional approach, b) one piece of material – the integral element

Thus, development of an innovative incremental forming process seems to be the best solution to obtain integral elements with required properties and without large amount of scraps. Possible solution is an incremental bulk forming process that enables receiving shapes impossible to obtain from conventional forging methods. Exaggerated loads recorded on the presses during conventional forging can be eliminated by division of the die into a series of small anvils that realize complex deformation in a sequential manner as seen in Fig. 2 [3]. Such technology can be also successfully used to manufacture products from materials that are considered as a hardly deformable [3]. What is more, incremental forming process, enables to obtain integral elements during one process, without additional finishing as well as assembly operations.



Fig. 2. Idea of an incremental forming approach

However, as seen in Fig. 2 the incremental forming concept is more complicated from technological point of view and requires development of new presses capable to forge subsequent anvils into the material. Therefore, to simplify the problem authors proposed in

[3] the incremental forming process enriched only by an additional die in the form of a roll with back and forth movement, that exerts load on subsequent anvils, what gives a possibility to use conventional available forging presses. The roll that moves from one side to the another and backwards, presses consecutive anvils into the deformed material. Schematic illustration of the proposed technology is presented in Fig. 3.



Fig. 3. Illustration of developed incremental forming process [4]

Nevertheless, before this innovatory process can be applied into industrial conditions, a detailed knowledge on mechanisms that control deformation and microstructure evolution during mentioned complex conditions is needed. Experimental studies are usually employed to provide such knowledge, but they are very expensive and time consuming, especially when material behavior at the microstructure scale is investigated. This problem can be solved by applying numerical approaches, which are less expensive and can support as well as broaden an experimental analysis. Although, most of numerical models, currently used in industry predict, material behavior only at the macroscale level, without taking into account local material behavior at the microstructure level [5]. In the case of mentioned innovative incremental forming technologies, local inhomogenous material behavior at the level of subsequent grains cannot be neglected. That is why, the objective of the paper is development of the complete multiscale numerical model of the incremental forming process, based on the Digital Material Representation (DMR) concept.

## 2. MULTISCALE ANALYSIS OF MATERIAL FLOW DURING INCREMENTAL FORMING PROCESS

Conventional methods of computer calculations are based on material data that are uniformed in the whole specimen volume and they provide only general information regarding e.g. strain distribution across the sample [6],[7],[8]. The underlying microstructure is not taken explicitly into account in this case. On the other hand, results obtained from the experimental approach clearly show how complex underlying microstructure can be. Lack of detailed information regarding material behavior from conventional numerical approach at the micro scale level is evident.

The mentioned digital material representation concept enables a detailed description of a real material morphology, where different micro scale features are included, e.g. precipitates, inclusions, big and small grains, grain boundaries, crystallographic grains orientations, phases boundaries, etc. as presented in Fig. 4.



Fig. 4. Digital material representation concept a) morphology, b) finite element mesh generated with the *DMRmesh* software [9]

The more precise the DMR is applied, the more realistic results of calculations regarding material behavior are obtained, what can be proven by research made all over the world [10],[11],[12],[13],[14],[15]. Due to that conclusion, the detailed virtual analysis of real material behavior can be performed, while errors of calculations are minimized. Numerical models based on the DMR give more detailed results, than those, which are based on conventional approaches. That is why, application of the DMR concept is so important, as it provides a possibility to take the complex microstructure into account in an explicit manner [6],[7],[8].



Fig. 5. Concept of the multiscale concurrent model

The DMR models are often used in multiscale solutions that predict global material behavior as well as can analyze microstructure changes during deformation in some critical/interesting locations, e.g. where the material failure or delaminating can be observed. There are various approaches to multiscale modeling, that can be classified into two groups: upscaling and concurrent ones [16].

The concurrent multiscale computing used in the present research is based on the assumption that several length scales are investigated at the same time by an *a priori* decomposition of computational domain as seen in Fig. 5. The two scale coupling where both macro and micro scales are described by the finite element method was used within the present research.

In the present work, five micro scale DMR models containing 100 grains are attached in various interesting locations selected in the macro scale finite element model (Fig. 6). Both incremental and conventional forging processes where modeled to highlight differences between them. The data transfer between scales is made by an interpolation of displacement boundary conditions from the macro to micro scale models.



Fig. 6. Illustration of the multiscale numerical model of a) incremental forming with 3 anvils and moving roll,b) conventional forging with one die, c) DMR model with 100 grains, d) finite element mesh generated with the *DMRmesh* software [9]

Developed numerical model consists only of 3 anvils pressed by the moving roll into the material 0.2mm in each indentation until the total indentation depth of 0.8 is reached. Thus, anvils are subsequently pressed into the sample from one side to the another and backwards two times. Specimen and anvils dimensions are  $50 \times 20$ mm and  $5 \times 10$ mm, respectively. An aluminum Al99 material flow stress model, which is described by the Hansel-Spittel equation, was used during the investigation:

$$\sigma = A e^{m_1 T} \varepsilon^{m_2} e^{m_4 / \varepsilon} \dot{\varepsilon}^{m_3} \tag{1}$$

where:  $\sigma$  - flow stress;  $\varepsilon$  – equivalent strain;  $\dot{\varepsilon}$  - equivalent strain rate; *T* - temperature in °C; model coefficients: *A*=161.96332, *m*<sub>1</sub>=-0.00209, *m*<sub>2</sub>=0.22305, *m*<sub>3</sub>=0.01851, *m*<sub>4</sub>=0.00435.

Obtained results in the form of strain distributions for macro and micro scales are presented in Figs. 7, 8, 9 and Fig. 10.



Fig. 7. Strain distribution at the macro scale after incremental forging on 0.8mm depth



Fig. 8. Strain distribution at a macro scale after conventional forging on 0.8mm depth (scale is shown in Fig. 7)

Obtained results at the macro scale level clearly show that in a conventional forming with one large die, strains along the deformed surface are lower than in an incremental forming with 3 smaller anvils. Given results indicate that more detailed analysis of material flow in incremental forming process should be done using the micro scale models located in these areas as seen in Fig. 9.



Fig. 9. Comparison of strain distribution obtained after conventional forging and incremental forming in corresponding micro scale models

Inhomogeneous material flow is clearly visible at the micro scale level. Strain values in the model with incremental forming are much higher in the areas between anvils. The initial shape of the DMR model located directly under the bottom anvil is maintained after the deformation, what is not the case when other micro scale models are considered. Shapes of the first and the last DMR model are symmetrical and compatible with the material flow at the macro scale. However, the second and the fourth micro model shapes differ from the others. Also strain values across them are much higher in comparison to other DMRs. This is the results of material flow due to incremental movement of anvils pressed by the roll from one side to the other and backward, what cannot be observed in conventional forging. These inhomogeneities will influence material properties of the final product. Contrary, conventional forging process shows different material behavior when forming with one large die is investigated. Obtained strain distributions across microstructures located under the anvil are stable and values are very low. The strain localizes only in narrow zones at the corners of the pressed die.

### **3. CONCLUSIONS**

The aim of work was to analyze material behavior deformed during incremental forming process and conventional forging by using multiscale approach connected with the DMR concept. Analysis of material flow was investigated for 3 anvils pressed into the material by the roll with reciprocating movement. After detailed analysis of obtained results it can be concluded that:

- in the conventional forming strain accumulates in the corners of the indent, what will lead to significantly inhomogeneous material properties distribution,

- strain values in the incremental forming are much higher than in conventional one in the areas underneath anvils,

- more uniform strain accumulation in the deformed material in the case of incremental forming gives an opportunity to control its properties during the manufacturing stages,

- during incremental forming process, material between anvils is pushed from one side to the other what causes changes in grains shape at the micro scale level,

- multiscale numerical model based on the digital material representation concept can be used to evaluate local microstructure behavior, and can support development of incremental forming technology.

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