Journal of Machine Engineering, Vol. 14, No. 1, 2014

incremental forming,
integral elements,
numerical modelling

Joanna SZYNDLER[1]
Lukasz MADEJ[1]
Franciszek GROSMAN[2]

COMPUTER AIDED DEVELOPMENT OF THE INNOVATIVE INCREMENTAL FORMING PROCESS

Computer aided design of innovative incremental forming process dedicated to manufacturing integral elements for aerospace industry is the main aim of the present work. Description of the proposed incremental forging idea as well as details of the developed numerical models are presented within the paper. First, a simple model of a single anvil indentation was created to evaluate material behaviour under different pressing depths. Then a complete numerical model of developed incremental forming press was proposed. Finally, obtained results in the form of strain distribution and recorded forging loads are presented and compared with results from conventional forming model.

1. INTRODUCTION

Due to the rising necessity of natural environment protection, new environmentally friendly products and manufacturing technologies are presently in high request. Due to very strict European Union regulations there is a necessity to reduce carbon dioxide and noise emissions as well as electricity consumption during subsequent manufacturing stages. At the same time customers demand reduction in prices (production costs) and improvement in the quality of products. One of the possible solutions to meet these requirements, is reduction in weight of the commonly used conveyances (i.e. cars, trucks, airplanes, transport aircrafts). This gives a possibility to reduce e.g. the amount of consumed fuel and in consequence to reduce the amount of carbon dioxide emission into the atmosphere. A worldwide environmental protection policy insists on limitation of factors that are dangerous for the natural environment, what can be especially seen in goals of the European Framework Program of Research and Innovation (2014-2020) – Horizon 2020. One of the main goals of this program is the production of greener and quieter aircrafts, vehicles and ships that will contribute to the improvement of environmental protection by noticeable reduction in noise and vibration emission. However, research is mostly concentrated on reduction in emission of harmful substances, produced by an air transport. Such works can be clearly visible in 7th

[1] AGH University of Science and Technology, Cracow, Poland, E-mail: joanna.szyndler@agh.edu.pl
[2] Silesian University of Technology, Gliwice, Poland

Framework Program projects: NINHA, X-NOISE EV, MARS or DAEDALOS. As mentioned, one of the suggested solutions is the successive decrease in aircrafts weight by using lightweight non-metallic composites. However, not every part of the construction can be made from these lightweight materials. This is clearly visible in case of structural parts, which are crucial from the safety point of view and have to be characterized by high durability and load carrying capacity. In these applications metallic materials are still widely used to manufacture subsequent components, then assembled and joined together in the final product that is used in the air plane construction. To reduce weight of these assembled parts a so called integral parts made from lightweight alloys, i.e. aluminum, titanium or magnesium can be introduced. Integral elements are made from one piece of material, which is equivalent to the product that in a conventional approach is made from many smaller parts [1]. Avoidance of joints (welds, rivets), which weaken the whole part, causes that the product is lighter, more durable and less susceptible for cracking in vital locations during exploitation. Integral parts idea is presented in Fig. 1.

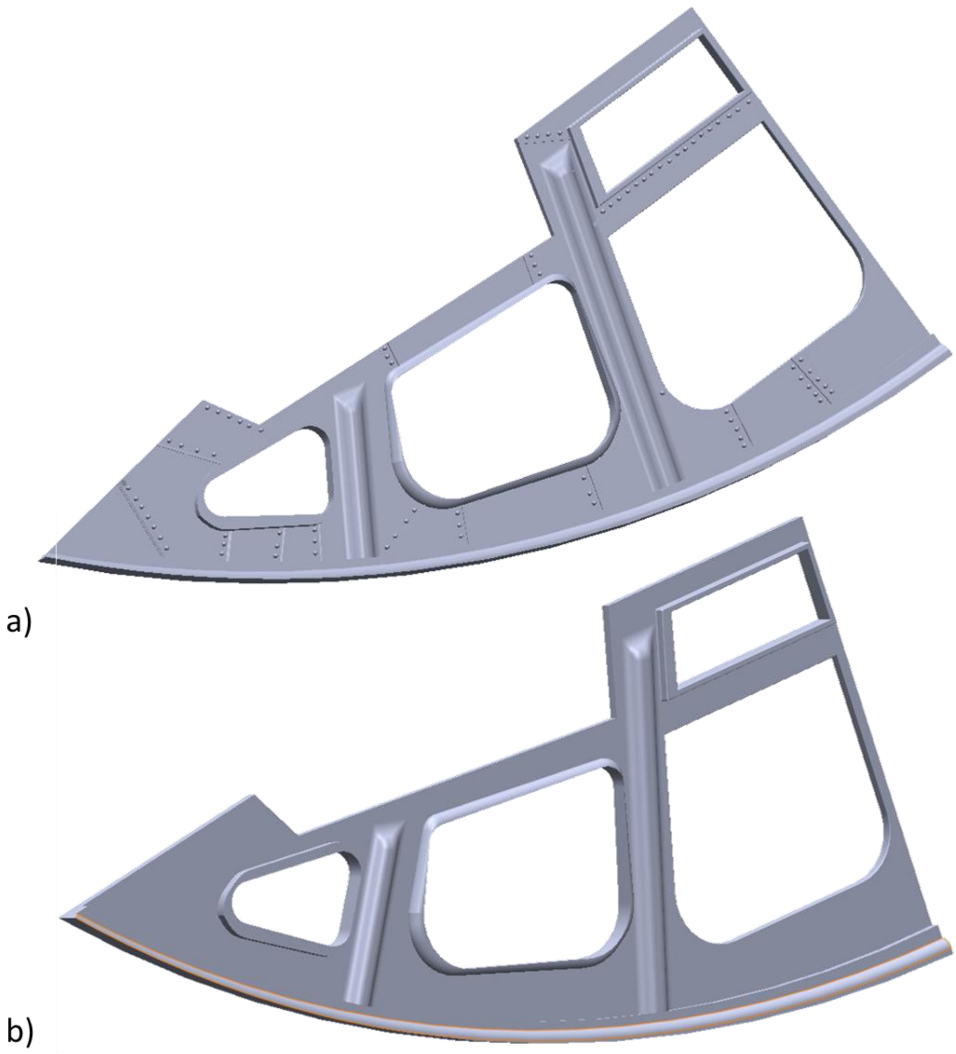

Fig. 1. Example of a part made from a) many smaller elements in a conventional approach, b) one piece of material – integral element [1]

Application of integral elements in aerospace industry also enables to reduce exploitation costs of other airplane components (i.e. tires), what extends their lifespan and lowers conservation costs and production outlay even up to 40% [1]. The next very important aspect of forming technology used during manufacturing of integral parts is a reduction of used energy, because smaller quantity of components has to be manufactured. As presented, advantages of mentioned integral parts are vast. Unfortunately, because of complicated shapes and large area sizes, forming of such components with traditional forging methods is practically impossible [1]. That is why, to obtain integral parts, a series of manufacturing technologies based on machining, rolling, extrusion or casting were developed in recent years [1]. Regrettably, most of them are connected with high costs and technical problems, small efficiency or limited applications. Therefore, development of an innovative incremental forming process seems to be the best solution to obtain integral elements.

2. INCREMENTAL FORGING

Incremental forming enables obtaining shapes impossible to get by conventional forming methods. Processes of an incremental forming can be divided into two main groups: the sheet forming [2-6] and the bulk forming [7–11]. Examples of commonly used incremental forming processes are presented in Fig. 2 and described in [12],[13].

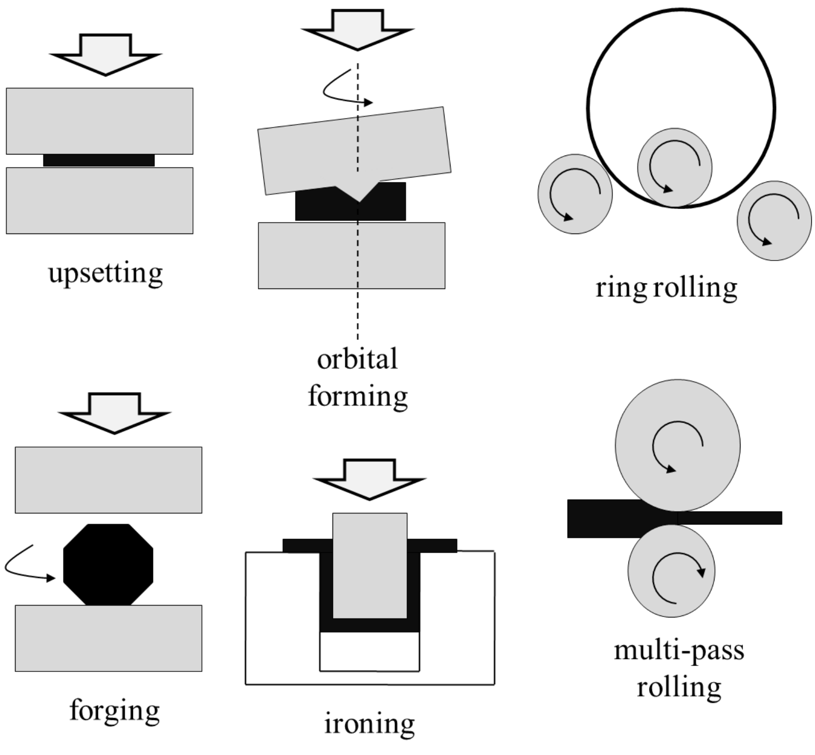

Fig. 2. Examples of incremental forming processes

The process of incremental forging is another interesting example. Incremental forging enables to eliminate excessive loads recorded on the presses during e.g. conventional forging, by division of the die into a series of small anvils that realize complex deformation in a sequential manner as seen in Fig. 3. This idea was proposed by Grosman et al. in [12]. Such technology can also be successfully used to manufacture products from materials that are considered as a hardly deformable [12].

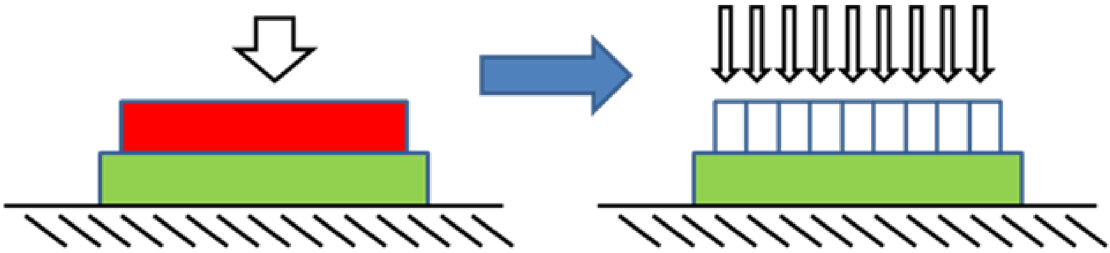

Fig. 3. Idea of an incremental forming approach

The main advantage of using incremental forming is possibility to lower expected press loads and to increase material deformation limits. Accordingly, based on the experience gained during previous author's work [12], it was decided to develop an innovative process of incremental forming of integral elements dedicated to aerospace industry. The new idea for obtaining ecological and environmental friendly integral elements is based on combination of incremental forming with additional die in the form of roll with reciprocating movement, that exerts load on subsequent anvils. The roll that moves from one side to the other and backwards, presses subsequent anvils into the deformed component. This approach enables obtaining thin parts with additional strengthening ribs. Schematic illustration of the proposed technology is presented in Fig. 4.

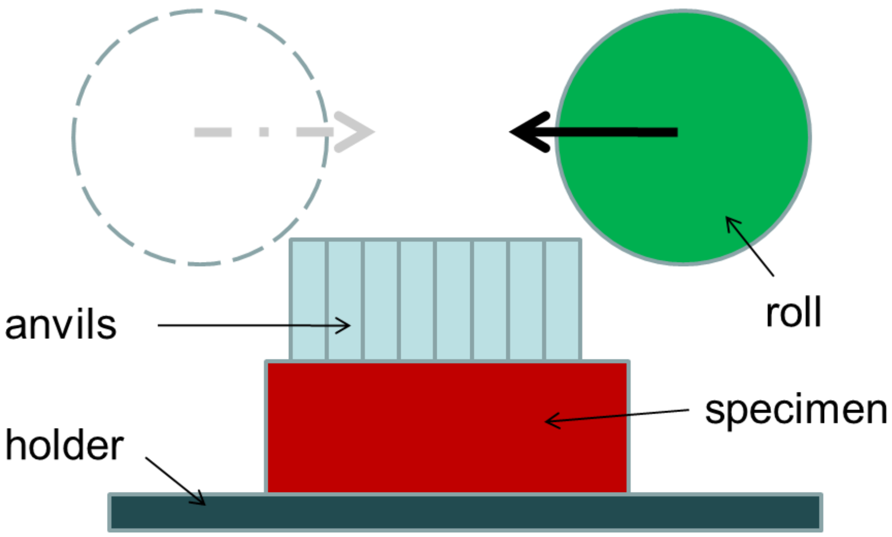

Fig. 4. Illustration of developed incremental forming process [13]

However, to successfully apply these innovative forming technologies at the industrial scale, engineers have to gain detailed knowledge on mechanisms that control deformation and microstructure evolution during these complex conditions. 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 approach, which is less expensive and can support and broaden an experimental analysis. To support the laboratory research [13] it was decided to develop a set of computer models capable to replicate experimental observations. At first, a simple model of single anvil indentation was created to evaluate material behavior under different pressing depths. Then, a complete numerical model of developed incremental forming press was proposed. The model will be used to determine the technological parameters ensuring the required quality of the finished product.

3. ANALYSIS OF MATERIAL FLOW DURING PLASTIC DEFORMATIONS WITH SINGLE ANVIL

To make a detailed analysis of material behavior in the area of subsequent anvils, series of calculations were realized to evaluate the appropriate depth of the single anvil indentation under one roll pass. For this reason, a simple two dimensional model was proposed. In the case, a single anvil is pressed into the material up to 10 different depths: 0.1, 0.2, 0.3, 0.4, 0.5, 1, 2, 3, 4 and 5mm. The anvil dimensions and sample dimensions are 5 × 10, 25 × 10 mm, respectively. An aluminum Al99 material flow stress model, which is described by the Hansel-Spittle equation, was used during the investigation:

$$\sigma = Ae^{m_1 T}\varepsilon^{m_2}e^{m_4/\varepsilon}\dot{\varepsilon}^{m_3} \quad (1)$$

where: σ - flow stress; ε – equivalent strain; $\dot{\varepsilon}$ - equivalent strain rate; T – temperature in ˚C; model coefficients: A=161,96332, m_1=-0,00209, m_2=0,22305, m_3=0,01851, m_4=0,00435 were taken from the Forge material data base.

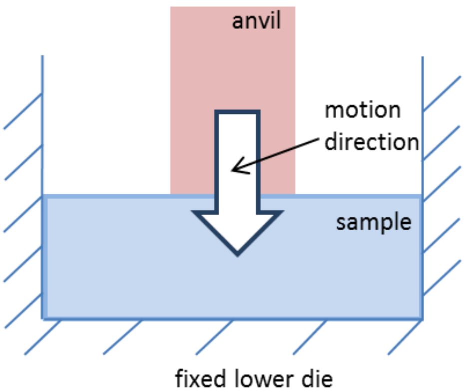

Fig. 5. Illustration of the numerical model of a single anvil indentation

The goal is to determine the depth that will decrease the forming time and, at the same time, will not significantly deform the surrounding material. The surface next to the anvil should be as uniform as possible, otherwise it will lead to no uniform wear and failure of subsequent anvils. Numerical simulations were performed in Forge2 finite element software. A schematic illustration of the proposed model is presented in Fig. 5. Obtained results in the form of strain distributions and surface shapes are presented in Fig. 6 and 7, respectively.

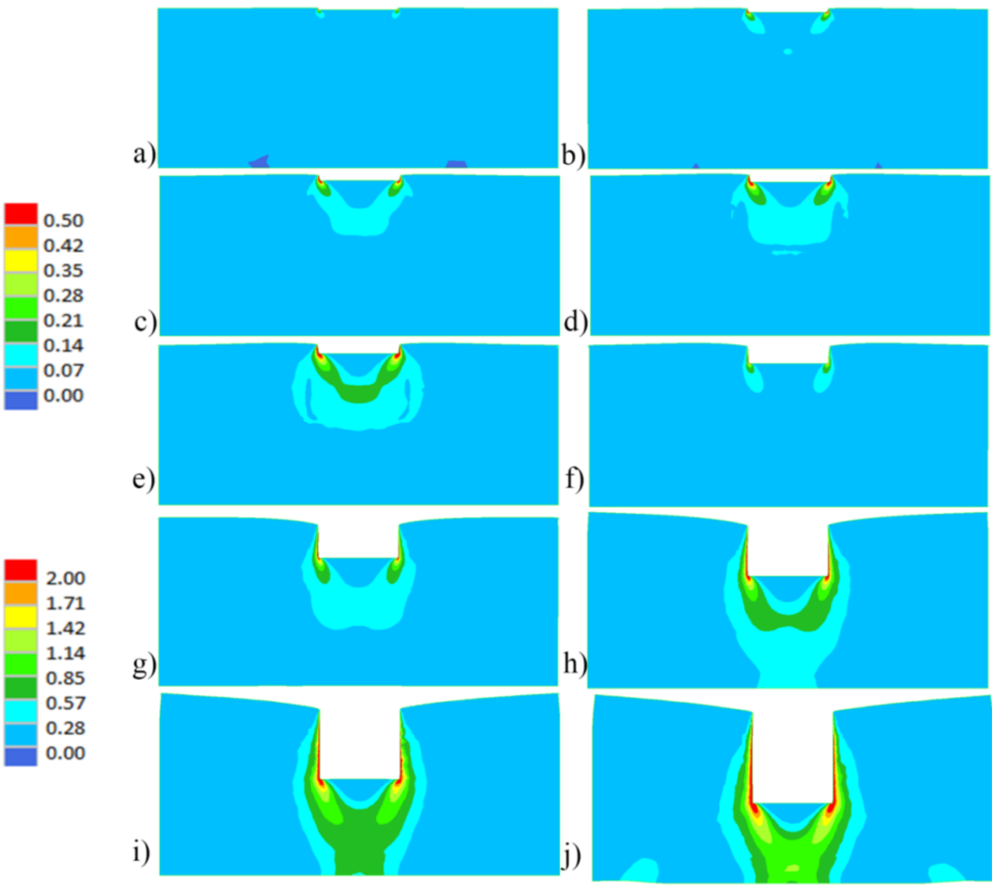

Fig. 6. Strain distribution after indentation depth: a) 0.1mm, b) 0.2mm, c) 0.3mm, d) 0.4mm, e) 0.5mm, f) 1mm, g) 2mm, h) 3mm, i) 4mm, j) 5mm. Cases from 0.1mm to 0.5mm depth are presented according to the upper scale, the rest is presented according to the lower scale

Results presented in Fig. 6 clearly show that, the depth of the zone beneath the anvil that is affected by the indentation is quite large, even for smaller indentations. Obtained results expose also a positive effect of dragging material on both sides of an anvil and negative effect of material bulging at the top surface (Fig. 7). With smaller indentation values the surface of the sample behaves more stable and its shape is similar to its initial form. It can be observed that bigger indentation depths causes severe bulging of the surface, what may lead to problems during incremental forming process e.g. overflows or uneven anvil wear. At the same time it is expected to have the highest possible indentation depth, because of priceless manufacturing time. Thus, it can be concluded that 0.5mm depth is the highest possible indentation depth. Below that depth top surface behaves stable without significant bulging. This limit was used during further analysis.

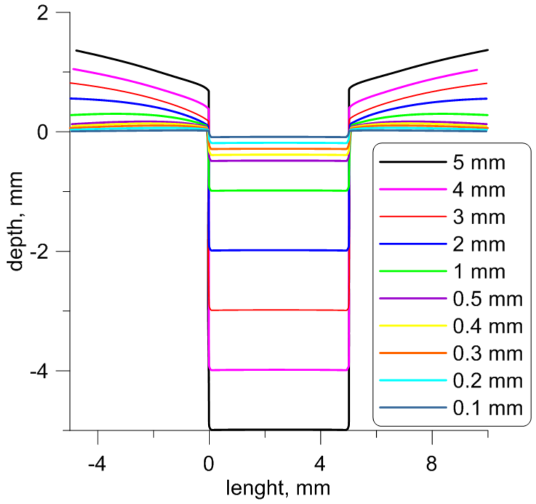

Fig. 7. Shapes of the upper part of the sample after pressing an anvil to different depth

4. ANALYSIS OF MATERIAL FLOW IN INCREMENTAL FORGING PROCESS

The developed numerical model consists of 6 anvils pressed into the material by the moving roll. Four passes of working roll were applied, with frequency equals 0.5Hz and the pressing depth per pass 0.5mm. As mentioned, such indentation depth provide acceptable manufacturing time and reduces probability of e.g. material overflows. Specimen and anvils dimensions are 50 × 20mm and 5 × 10mm, respectively. Dimensions of the model are presented in Fig. 8. In the investigated case study, the material flow is constrained on both

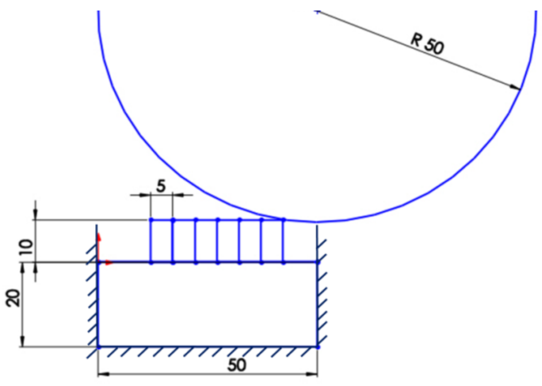

Fig. 8. Simulation setup of the developed incremental forming process

sides of the sample to produce strengthening ribs due to the backward extrusion. As previously, the aluminum Al99 material flow stress model was used.

Obtained results in the form of strain distribution obtained after each pass are shown in Fig. 9. Comparison between load recorded in the incremental and conventional forming for the same process conditions is presented in Fig. 10.

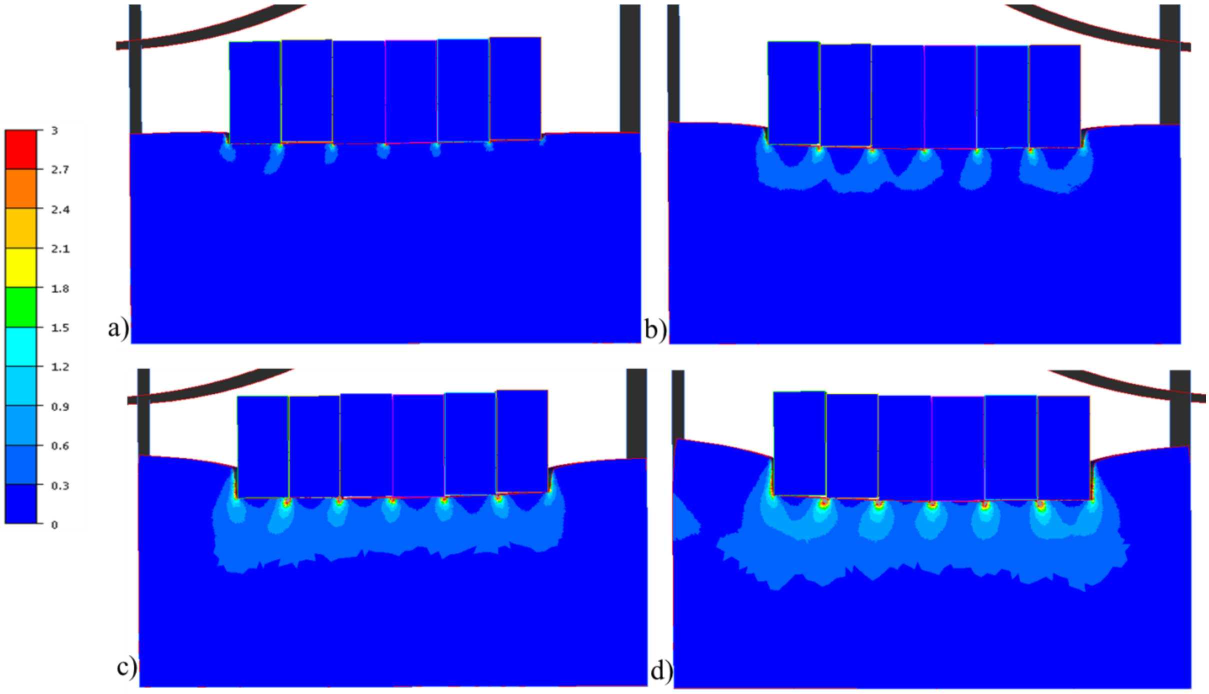

Fig. 9. Strain distribution after incremental forming process with 6 anvils after a) 1st, b) 2nd, c) 3rd and d) 4th roll pass

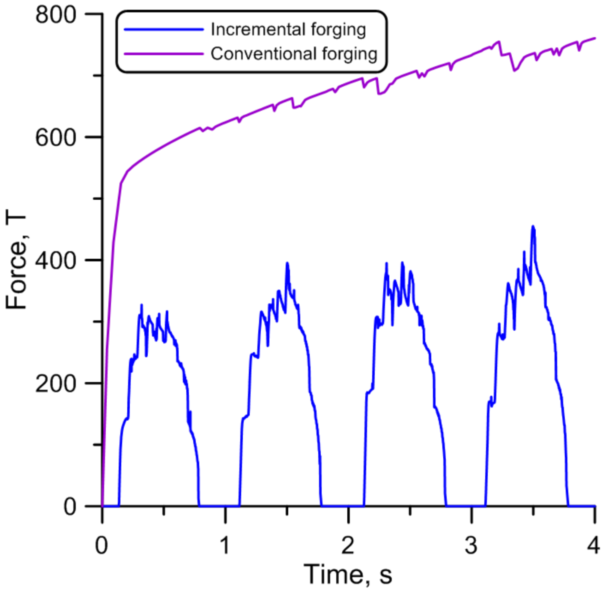

Fig. 10. Loads recorded during conventional and incremental forming

Results in Fig. 9 clearly show that during incremental forming, the strain values rise in the areas between anvils due to the strain path change effect. However, in general, material deformation is quite uniform across the sample. Comparison of loads presented in Fig. 10, clearly highlights the main advantage of the new process – reduction in loads required for material deformation. During the incremental forming, maximum recorded load is 40% lower than in the conventional forming. It is expected that this reduction will be even higher when smaller diameter of working roll will be used. Oscillations of load values, visible during subsequent roll passes, are due to different number of anvils that are simultaneously pressed into the material. Presently used roll can be in contact with maximum three anvils at the same time.

Presented initial results prove that innovative incremental forming process has a large potential in application to forming of integral elements for aerospace industry.

5. CONCLUSIONS

The aim of this work was a numerical analysis of material flow during innovative incremental forming process. The analysis of material behavior was performed in the 2D space for different indentation depths of a single anvil and for a more complex model with 6 anvils and the moving working roll. Obtained results expose positive effect of dragging material on both sides of an anvil and negative effect of excessive material bulging at the surface of the sample. A robust process window in case of indentation depth was established between 0.1 and 0.5 mm per roll pass. Results obtained from complete incremental forming model prove that a significant decrease in forging loads can be obtained. Present press setup provides 40% reduction in applied load. It is expected that this can be controlled by proper selection of working roll radius. Other process parameters e.g. roll size, roll velocity or frequency will be evaluated during future work.

ACKNOWLEDGEMENTS

Financial support of Structural Funds in the Operational Program - Innovative Economy (IE OP) financed from the European Regional Development Fund - Project "Modern material technologies in aerospace industry", Nr POIG.01.01.02-00-015/08-00 is gratefully acknowledged.

REFERENCES

[1] WIŚLICKI T.; 1964, *Airframe construction technology*, Wydawnictwa Naukowo – Techniczne, Warszawa, (in Polish).

[2] HUSSAIN G., GAO L.; 2007, *A novel method to test the thinning limits of sheet metals in negative incremental forming*, International Journal of Machine Tools & Manufacture, 47, 419–435.

[3] ISEKIA H., NAGANAWAB T.; 2002, *Vertical wall surface forming of rectangular shell using multistage incremental forming with spherical and cylindrical rollers*, Journal of Materials Processing Technology, 130–131, 675–679.

[4] HUSSAIN G., GAOA L., DAR N.U.; 2007, *An experimental study on some formability evaluation methods in negative incremental forming*, Journal of Materials Processing Technology, 186, 45–53.

[5] YOON S.J., YANGL D.Y.; 2005, *An incremental roll forming process for manufacturing doubly curved sheets from general quadrilateral sheet blanks with enhanced process features,* CIRP Annals - Manufacturing Technology, 54, 221-224.

[6] FILICEL L., FRATIN L., MICARI F.; 2002, *Analysis of material formability in incremental forming*, CIRP Annals - Manufacturing Technology, 51/1, 199-202.

[7] MUSZKA K., MADEJ L., MAJTA J.; 2013, *The effects of deformation and microstructure inhomogeneities in the Accumulative Angular Drawing (AAD)*, Materials Science and Engineering A, 574, 68-74.

[8] STANISTREET T.F., ALLWOOD J.M., WILLOUGHBY A.M.; 2006, *The design of a flexible model ring rolling machine*, Journal of Materials Processing Technology, 177, 630–633.

[9] GROCHE P., FRITSCHE D.,TEKKAYA E.A., ALLWOOD J.M., HIRT G., NEUGEBAUER R.; 2007, *Incremental bulk metal forming*, CIRP Annals - Manufacturing Technology, 56, 635–656

[10] WONG C.C., DEAN T.A., LIN J.; 2004, *Incremental forming of solid cylindrical components using flow forming principles*, Journal of Materials Processing Technology, 153–154, 60–66.

[11] JIN Y., MURATA M.; 2004, *Influence of pitch and cross-sectional ratio of strip of sheet metal on incremental in-plane bending*, Journal of Materials Processing Technology, 155–156, 1810–1814.

[12] GROSMAN F., MADEJ L., ZIOLKIEWICZ S., NOWAK J.; 2012, *Experimental and numerical investigation on development of new incremental forming process*, Journal of Materials Processing Technology, 212, 2200–2209.

[13] GROSMAN F., TKOCZ M., PAWLICKI, J. LIPSKA B.; 2012, *Incremental forming of integral parts*, Hutnik – Wiadomości Hutnicze, 8, 583-586, (in Polish).