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METALFORMING METHODS DEDICATED FOR AEROSPACE INDUSTRY

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Abstract

Detailed analysis of different metalforming methods of light and durable integral elements dedicated for the aerospace industry is the main aim of the work. Description of an integral part concept as well as basis of conventional processes used for their manufacturing are presented within the paper. Then incremental forming processes with a division into sheet and bulk metal forming methods are precisely described. State of the art both in experimental and numerical research on these processes is discussed within the paper. Finally, recent concept of an alternative incremental forming process dedicated for manufacturing integral elements from lightweight alloys is presented. Particular attention is put on computer aided support of development of the innovative forming technology.

Key words: metalforming, incremental forming, multiscale numerical modelling, integral elements

1. INTRODUCTION

In recent years natural environment becomes more and more endangered by different sources of pollution. The rising necessity of its protection is one of the driving forces for development of new materials as well as innovative manufacturing solutions. As a consequence rigorous European Union regulations for carbon dioxide and noise emissions as well as electricity consumption during subsequent production stages and further exploitation conditions have to be enforced. A worldwide environmental protection policy insists on limitation of factors that are dangerous for 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 objectives of this program is production of greener and quieter aircrafts, vehicles and ships. It is expected that this will contribute to the improvement of environmental protection by noticeable reduction in noise, vibrations and emission of harmful substances produced by an air and ground transport.

One of the opportunities to meet mentioned requirements, is reduction in weight of the commonly used conveyances (i.e. cars, trucks, airplanes, transport aircrafts). That gives possibility to reduce e.g. the amount of consumed fuel and in consequence to reduce the amount of carbon dioxide emission into the atmosphere.

Thus, there is a need to reduce weight of vehicles, but at the same time customers demand reduction in prices (production costs) and improvement in the quality of products. Also restrictions of passengers welfare becomes tighter and customers’ expectations raises, so the vehicles safety features are constantly enriched, what in consequence increases the overall mass of conveyances. During years different solutions were proposed to address the question of how to lower the vehicle weight. The first, is to develop new, advanced steels, aluminum alloys, magnesium alloys, carbon fibers, composites or plastics that can be applied to construct the final

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product (Smojver & Ivancevic, 2010). The second, is to replace some constructional parts with lighter tailored blanks or tailored tubes (e.g. B – pillars in cars) that can have different properties in different zones (Merklein et al., 2014). Also a fuel reduction can be obtained by better optimization of chassis or fuselages, by e.g. using numerical simulations. Another recent idea is to design new methods of material forming that can provide better products specifically designed for particular application (Ding et al., 2011). Finally, the last concept that can be used to reduce weight and increase safety of constructional elements is to replace several components that were joined together with an integral element, made from one piece of material. The last two approaches are pursuit in detail within the present work, where development of innovative forming process of integral elements is presented.

2. INTEGRAL ELEMENTS

In the conventional approach, many constructional elements e.g. in fuselage, are made from several smaller components that are somehow joined (welded, riveted) (Wiślicki, 1964). Unfortunately, these joints weaken the final part, and may cause failure initiation within these areas. The easiest solution to prevent this behavior is to replace these complex constructional elements with integral parts, that are made from one piece of material (figure 1). Integral element is lighter, more durable and less susceptible for cracking in vital locations during exploitation. Application of integral elements in an aerospace industry enables also reduction of exploitation costs of other airplane components (i.e. tires), what extends their lifespan and lowers conservation costs and production outlay even up to 40% (Wiślicki, 1964). Reduction of energy consumption during manufacturing stages, as less elements have to be manufactured, is another important aspect of forming technologies used during manufacturing of integral components.

As presented, advantages of mentioned integral parts are vast. Unfortunately, because of complicated shape and large area size, forming such components with traditional forging methods is practically impossible (Wiślicki, 1964). That is why different manufacturing technologies based on e.g. machining, rolling, extrusion or casting were developed in recent years to obtain integral parts as presented in figure 2 (Wiślicki, 1964). Regrettably, most of them are connected with high costs and technical problems, small efficiency or limited applications.

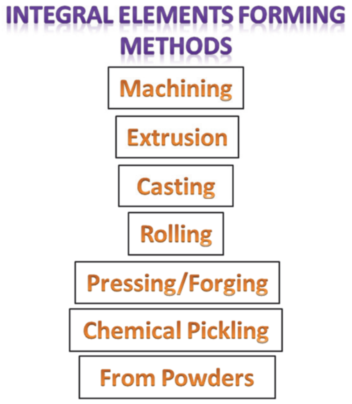

Fig. 2. *Methods of forming integral elements for the aerospace industry.*

3. FORMING METHODS OF INTEGRAL ELEMENTS

As seen in figure 2, forming methods of integral elements can be divided into seven general groups: machining, rolling, extrusion, pressing/forging, casting, chemical pickling and the recent technology based on powder metallurgy.

Machining is a broad term used to described removal of material from a workpiece. Generally can be divided into cutting (figure 3), abrasive processes such as grinding, or nontraditional processes i.e. utilizing chemical etchants, electrical or other sources of energy. Machining is the oldest method of manufacturing integral elements dedicated to the

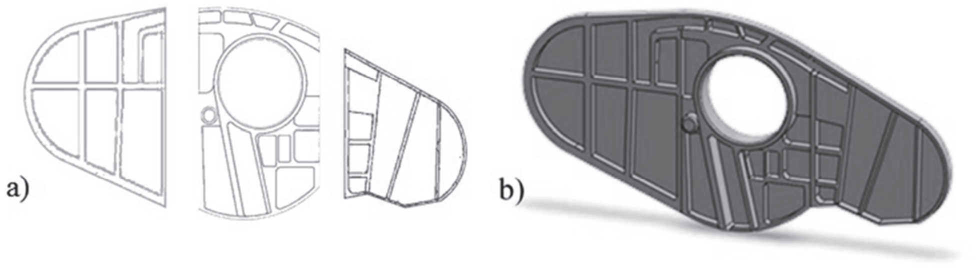

Fig. 1. *Comparison between a) conventional component and b) integral element concept.*

aerospace industry. To obtain large, flat and thin elements, that can replace many smaller parts in airplanes construction, an universal machines were developed, which unfortunately are quite expensive and complex in use. At the same time large quantities of material are wasted what results in small efficiency in obtaining integral elements. What is more this method can also be characterized by small accuracy of dimensions and shape when hard or high strength materials are processed.

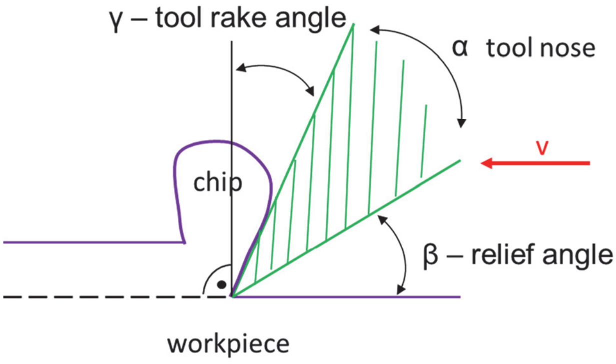

Fig. 3. *Schematic illustration of machining process and cheap formation.*

It is also economically and technically proven that machining is a good way of finishing treatment for elements that are obtained during other methods, e.g. forged or extruded. A lot of work on development of numerical models capable to simulate machining were published in scientific literature e.g. (Zenia et al., 2015; Poniatowska, 2015; Rotella & Umbrello, 2014), where Finite Element Method (FEM) and NURBS modelling where primarily used.

The easiest and fastest way of forming integral elements is shape rolling (figure 4). Rolling of metal sheet with stiffeners (figure 5) dedicated for the skin of airplane was the first step of introducing integral elements into the fuselage construction. Additional ribs provide a sheet that is characterized by a higher stiffness parameter, in comparison with the flat rolled product of the same mass. Ribbed sheet metal can then be deformed similarly as common sheet metal – it can be cut, bended, formed in two dimensions or stretched.

As a result these products are applied in different locations in the airframe construction e.g. a) skins of less loaded airplane elements, b) ribs, c) bottoms or walls of containers, d) dashboards, e) covers and doors, etc.

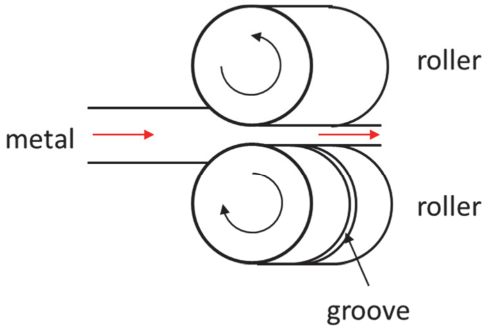

Fig. 4. *Schematic illustration of a rolling process.*

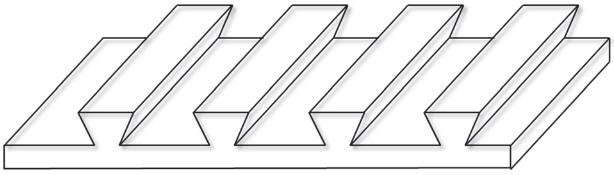

Fig. 5. *Schematic illustration of metal sheet with stiffening ribs.*

Unfortunately, with respect to forming integral elements, rolling method has some application limitations caused by difficulties with obtaining expected height and thickness ratio of stiffening ribs. Thus, the finite element method is most commonly used to support designing of such rolling technology that meets customers' expectations, see e.g. (Cawthorn et al., 2014; Sun et al., 2014; Pesin & Pustovoytov, 2014). Although simple slab theory model, the classic inhomogeneous model of Orowan (1943) and a more recent, mathematical approach introduced by Domanti and McElwain (1995) are also used.

Another popular method of obtaining semi-finished products for the aerospace industry is extrusion (figure 6). Looking from the technical aspect point of view, extrusion enables obtaining elements with a) complex shapes with small number of operations, b) high dimensional accuracy and smooth surfaces, c) considerable length, difficult to obtain by other methods and d) reduced weight in comparison with e.g. casting. Also from economical aspects there are few advantages of extrusion process, e.g. significantly lower cost of die preparation and forming final shape of the product and material savings by manufacturing near net shape products. The method of backward extrusion can be very easily applied to obtain integral elements with additional strengthening ribs, similar to the one after rolling or machining.

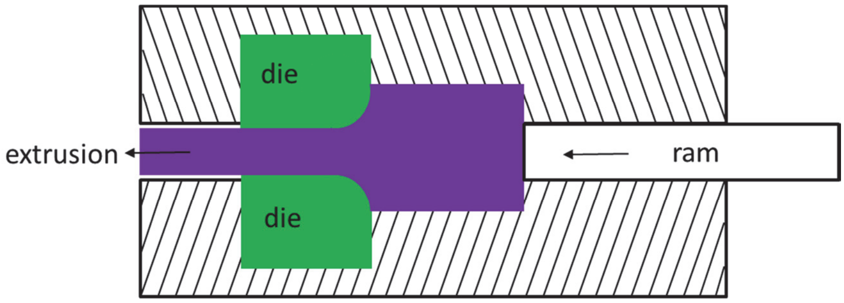

Fig. 6. Schematic illustration of a direct extrusion process.

Unfortunately, when room temperature deformation conditions have to be imposed to obtain proper final properties, there is a necessity to use extreme pressures, especially when large area parts are considered. That is a limiting factor of wider application of the method. Extrusion at the hot deformation conditions, enables to lower press loads, however as mentioned unfavorable decrease in material strength (Al alloys), smaller process productivity, surface oxidation and reduction in shape accuracy can be observed. Also too large extrusion velocity can cause significant stress increase and surface roughness, what requires application of additional finishing operations. All these issues were extensively tackled from numerical point of view. Different methods were applied to evaluate material behavior during the extrusion e.g. (Matsumoto et al., 2014; Mahmoodkhani et al., 2014; Tingting et al., 2014; Alharthi et al., 2014), where the most popular is the finite element method.

Another way of obtaining integral parts characterized by very good strength properties is pressing/forging (figure 7) (Schongen et al., 2014; Chval & Cechura, 2015; Luri et al., 2013). However, similar to extrusion, the technology is also connected with very big press loads that are required to obtain elements with wide dimensions. In comparison with machining, pressing and forging provides possibility to control mechanical properties of obtained elements and as a result lowers its final weight. Slightly, better precision can be reached by pressing in comparison to forging, what gives the possibility of employing staff with lower qualifications, and that is important from economical point of view.

Despite advantages of pressing/forging technologies, several problems can be identified during integral elements production. The first, is related with inaccuracy in filling the grooves for high and densely distributed stiffening ribs. The second, is associated with failure that may occur at the bottom of the rib due to high contact pressures with the die. Another problem is material distortion during cooling after hot forming due to e.g. phase transformations, what in consequences causes the necessity of application of additional finishing operations. These problems are mainly investigated with the FEM and Boundary Element Method (BEM) (Schongen et al., 2014; Chval & Cechura, 2015; Luri et al., 2013).

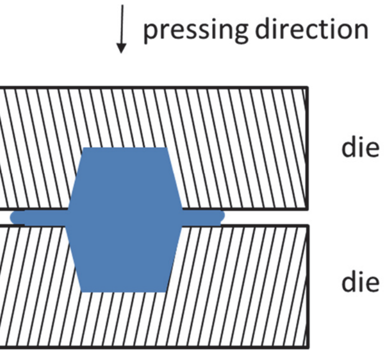

Fig. 7. Schematic illustration of a pressing process.

From economic point of view, casting (figure 8) is the best solution of obtaining integral parts with complex shapes. It can also be used to obtain large integral skins of airframes. The method is less time consuming than other methods, what in consequences enables to shorter the priceless production time. What is more, the weight of obtained elements can be lowered notably, if novel light materials are used. The benefit of casting method is also a very good weldability, machinability and runnability of liquid metal. Unfortunately, a lot of practical experience is needed to use casting method, because of problems connected with obtaining thin-walled parts and with shrinkage phenomenon, which lowers strength of casted parts. Also internal stresses can cause inhomogeneities in material structure.

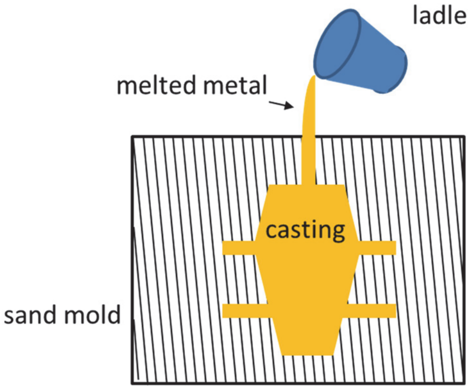

Fig. 8. Schematic illustration of a sand casting process.

Physical and anti-corrosion properties of casted parts, are very similar to properties of forged steel with the same chemical composition. However, it has to be emphasizes that significantly worst mechanical properties (lower elongation and impact resistance) caused by preservation of original structure of casting are obtained in comparison to e.g. forged components. Mentioned process is quite commonly simulated using the conventional finite element software (Jie et al., 2014; Bidhar et al., 2015; Bouzakis et al., 2012; Petrenko et al., 2014). However, more complex multi scale models taking into account microstructure evolution by Cellular Automata (CA) technique can also be found in scientific literature e.g. (Seo et al., 2007)

Another interesting method of manufacturing integral elements is a chemical pickling (figure 9) (Sohlberg, 2005), which is based on removing selected parts of metal by dipping the element in baths with corrosive properties. Zones that should remain unaffected during the pickling process are protected with special covers resistant to the etching factor.

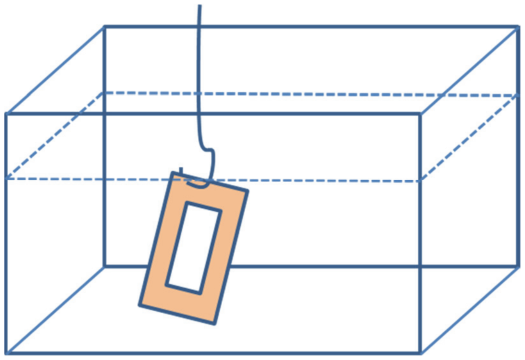

Fig. 9. *Schematic illustration of a chemical pickling process.*

Chemical pickling method has a lot of advantages, e.g.:

a) enables to form large and complex parts, conditioned only by apparatus dimensions,
b) easiness in treatment curved surfaces,
c) high quality of surface smoothness, with no necessity of additional treatment,
d) possibility of complete automation of the process,
e) no necessity of employing highly qualified staff.
f) The main disadvantage of chemical pickling is necessity of providing appropriate safety measures, more complicated than during machining or metalforming operations.

The most recent approach that is still under development is a group of processes connected with incremental manufacturing from powders (Qiu et al., 2015; Guo et al., 2015), which can also be named as additive fabrication, freeform fabrication, solid freeform fabrication or digital fabrication. Ways of fast manufacturing physical parts, prototypes or patterns from virtual 3D-CAD models, is called Rapid Prototyping (RP), while fast fabrication of forms or dies is named as Rapid Tooling (RT). Finally fast production of finished product is called Rapid Manufacturing (RM).

Incremental forming from powders enables to obtain rapid-prototypes at early stages of product manufacturing and almost completely eliminates necessity of additional and expensive treatment at later stages of production. Incremental forming can be used in the direct (RM methods) or indirect (RT methods) way.

The direct incremental forming can be realized by selective laser melting of metal powders (e.g. SLM, MTT, LaserCusing, LENS), electron beam melting metal powders (EBM process) or selective laser sintering metal powders (Direct Metal Laser Sintering - DMLS). The indirect incremental forming is used by RP to form casting models, e.g. for precision casting or with RT method to obtain forms and casting cores. Indirect forming methods involve stereolithography (that uses pointed, layered photopolymerization of liquid nanomer with laser radiation (SLA process) or UV light (Polyjet process)), selective laser sintering of moulding sands (Direct Croning Process – DCP) and selective three dimensional powder printing where powder particles are joined by sprayed layers of liquid binder (3DP process).

Incremental type processes also includes methods where different materials are applied on already formed surfaces, by using e.g. padding, metallization or coating application in different ways, to obtain wanted element properties. All methods of incremental forming from powders that were presented above, are schematically shown in figure 10.

As presented, different methods have their advantages as well as limitations. Thus, to solve some of mentioned problems with e.g. forging, fast development of modern incremental forming of sheet and bulk products is observed. Selected processes of incremental forming methods of solids are presented below.

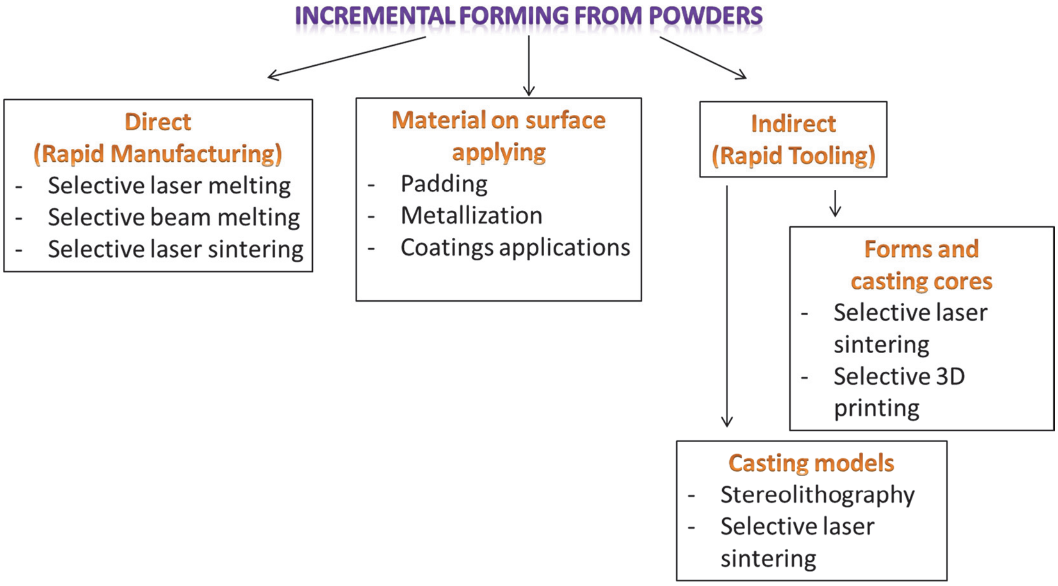

Fig. 10. Examples of incremental forming processes from powders (Oczoś & Kawalec, 2012).

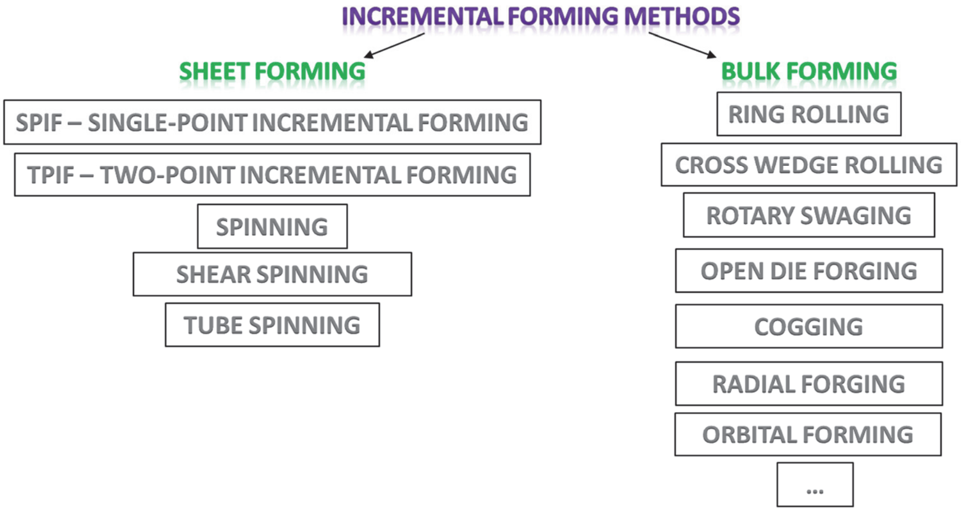

Fig. 11. Examples of incremental forming processes.

4. INCREMENTAL FORMING PROCESSES FROM SOLIDS

Incremental forming of metals enables obtaining shapes impossible to get from conventional metal forming methods. Processes of an incremental metal forming can be divided into two main groups: the sheet forming (Hussain & Gao, 2007; Isekia & Naganawab, 2002; Hussain et al., 2007; Yoon & Yangl, 2005; Filicel et. al., 2002) and the bulk forming (Muszka et al., 2013; Stanistreet et al., 2006; Groche et al., 2007; Wong et al., 2004; Jin & Murata, 2004). Examples of commonly used incremental forming processes are presented in figure 11.

One of the most widely researched process of incremental sheet forming is called Single-Point Incremental Forming (SPIF) (Guzman et al., 2012; Senthil & Gnanavelbabu, 2014; Malwad & Nandedkar, 2014). In the approach a sheet is clamped rigidly around its edges and formed by a single spherical-ended indenter (figure 12). Other variants of the process exist and are widely referred to as Two-Point Incremental Forming (TPIF), in which the sheet is formed against full or partial dies using one or more indenters.

The variants of the incremental sheet forming process setup also allow to form the sheet without any supporting tools, or with a full or partial die, or with a kinematical counter tool.

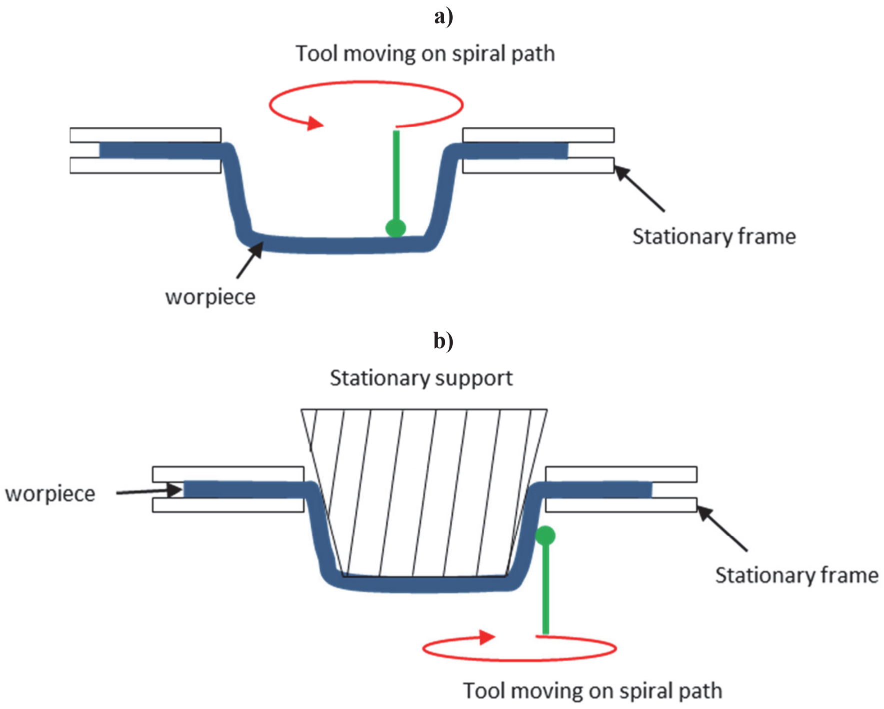

Fig. 12. *Schematic illustration of a a) Single Point Incremental Forming, b) Two-Point Incremental Forming process.*

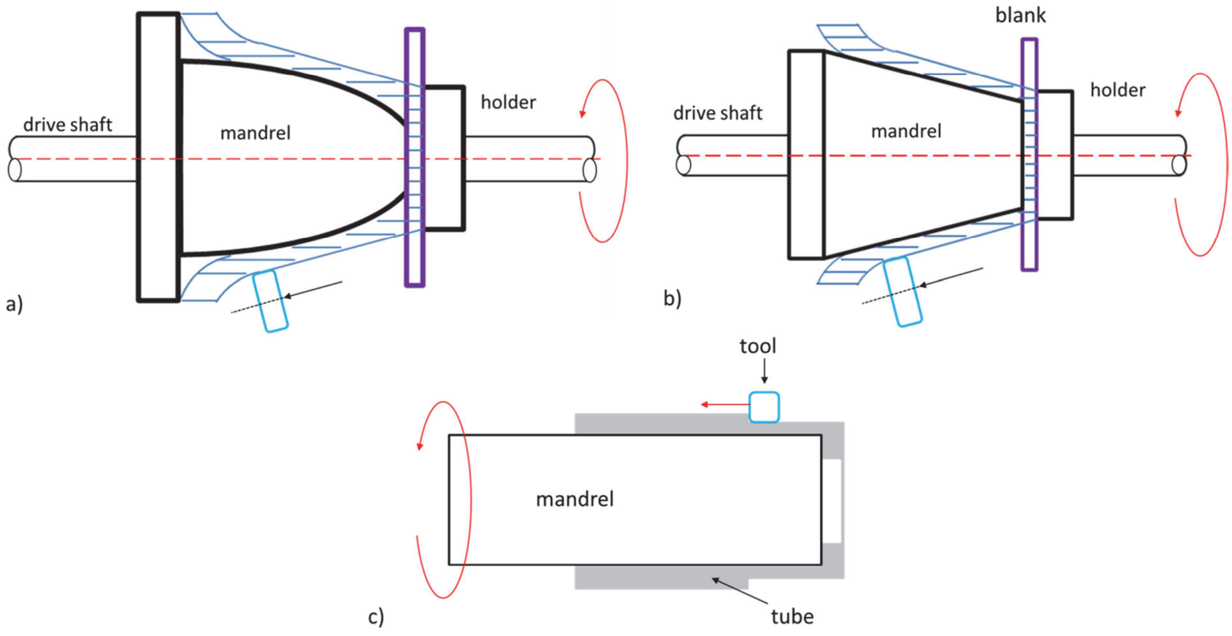

Fig. 13. *Schematic illustration of a) spinning, b) shear spinning, c) external tube spinning process.*

Another process of incremental sheet forming is spinning (Watson & Long, 2014; Xia et al., 2014) (figure 13a), also called spin forming. It is a metal forming process dedicated to obtain cylindrical parts by a rotating piece of sheet metal while forces are applied to one side. A sheet metal disc is rotated at high speeds while rollers press the sheet against a tool, called a mandrel, to form the shape of the desired part. Spun metal parts have a rotationally symmetric, hollow shape, such as a cylinder, cone or hemisphere. A variation of conventional spinning process is a shear spinning (Xia et al., 2014) method and is also known as flow turning or spin forging (figure 13b). Shear spinning involves forming the work over the mandrel, causing metal flow within the work, what will act to reduce the thickness of the work as it is formed. Contrary to the conventional spinning, the initial diameter of the work in shear spinning can be smaller. Limits to the amount of reduction of work thickness exist in order to prevent fracture. Coolants are normally used in shear spinning, since this manufacturing process can generate a lot of heat. One or two rollers may be used, where two will provide a better balance of forces during the operation. Shear spinning of some materials is often conducted at elevated temperatures.

The similar process to the shear spinning is a tube spinning (Xia et al., 2014) method (figure 13c). Again, the metal flow enables thickness reduction and length growth of formed cylindrical parts. This process can be performed externally with the tube over a mandrel or internally with the tube enclosed by a die. In some cases the die can be moved during the process in order to obtain features or contours on the inside/outside of the tube.

Despite the fact that incremental forming is usually related to sheet forming, more variety of processes with an incremental character can be found for bulk forming. The first, is a ring rolling process in which a ring of smaller diameter is rolled into a precise ring of larger diameter with a reduced cross section (figure 14). This is done by the use of two rollers, one driven and one idle, acting on either sides of the ring's cross section (Luo et al., 2014; Xiaotao & Fan, 2012; Parvizi & Abrinia, 2014; Malinowski et al., 2005).

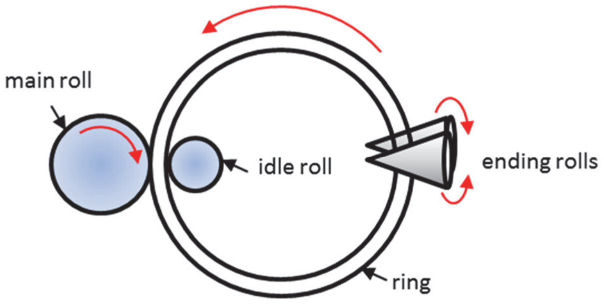

Fig. 14. Schematic illustration of a ring rolling process.

Edging rolls are typically used to ensure that the part will maintain a constant width throughout the whole forming operation. The workpiece will essentially retain the same volume, therefore the geometrical reduction in thickness will be counterbalanced by an increase in the ring's diameter. Ring rolling enables to obtain not only flat rings, but also rings of different cross sections. Another advantage is a possibility to produce very precise seamless parts with little waste of material. The most popular parts produced by ring rolling process are rings for machinery, aerospace industry, pipes, turbines, ball bearing races etc.

Another incremental process that uses rotating rolls is a cross rolling (Obayi et al., 2015) method (figure 15) which is a net-shape rolling process. It can be classified as high temperature incremental forming that gives cylindrical products through multi-step forming by rotating dies. During cross wedge rolling the billet spins as dies make one revolution and the contour on the die forces the billet material into the desired axi-symmetric preform shape (Liu et al., 2014; Wengfei et al., 2014). A variation is a process where dies are linear instead of round and they move past each other while rolling the billet between them.

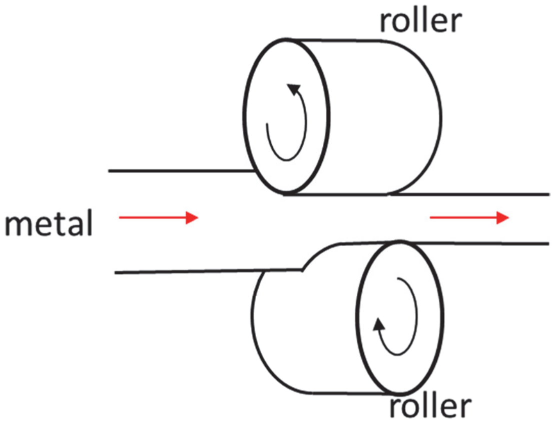

Fig. 15. Schematic illustration of a cross rolling process.

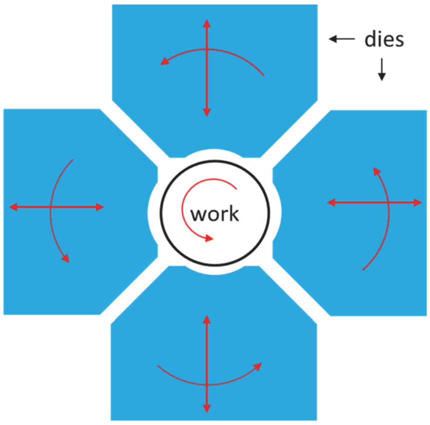

Fig. 16. Schematic illustration of a rotary swaging process.

Different kind of incremental forming process is a rotary swaging (figure 16), which is a process for precision forming of cylindrical workpieces e.g. tubes, bars, in many small processing steps (Zhang et al., 2014; Moumi et al., 2014). The forming dies of the swaging machine are arranged concentrically around the workpiece. The swaging dies perform high frequency radial movements with short strokes and applies compressive force onto the enclosed workpiece. Depending on the application, between two and eight dies can be used. Rotary swaging belongs to the category of net-shape forming processes, where the finished shape of the formed workpiece is obtained without, or with only a minimum amount of processing and cutting. In comparison to the continuous forming process, during rotary swaging the homogenous material properties are obtained, which is achieved by high forming ratios. Rotary swaging has all advantages of cold forming: reduced production time, close tolerances, continuous grain pattern, high surface quality, material savings and workpiece weight reduction.

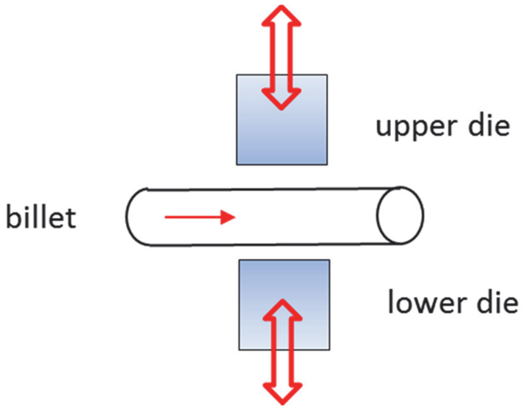

***Fig. 17.** Schematic illustration of a cogging process.*

Another group of incremental forming processes can be generally named as open die forging processes, where the work is compressed between two dies, that do not constrains the material flow during the deformation (Zahalka, 2014). Common open die forging process performed in industrial conditions, involves using flat die to round and elongate the ingot and is called cogging (figure 17). With the use of mechanical manipulators, a workpiece is compressed and rotated in a series of steps eventually forming the metal into a cylindrical or square shaped part. The compressions affect the material of the forging, closing up holes and gaps, breaking down and reforming weak grain boundaries as well as creating a wrought grain structure. As the open die forging process progresses the material of the part will be altered from the outside first and progressing inward. It is important that when manufacturing a metal forging, the part is worked enough to change the structure of the material in the center of the work piece. Large shafts for motors and turbines are forged this way from cast ingots (Song et al., 2014).

Cogging allows for smaller machinery with less power and forces to form preforms of great length. Often cogging may be just one of the metal forging process in manufacturing chain required to form a desired part. In case of modelling forging processes it can be seen that the most common is the FEM approach (Zahalka, 2014; Song et al., 2014).

One of the incremental forging process, that is commonly used at the industrial scale is the orbital forming (rotary forging) based on the Marciniak press concept (figure 18). In this technology a sample is placed between fixed lower die and an orbiting upper die that moves towards the sample (Feng et al. 2014; Nam et al., 2014). The lower die is properly shaped and gives final shape of the deformed workpiece.

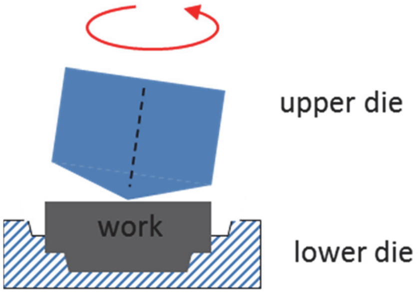

***Fig. 18.** Schematic illustration of an orbital forming process.*

Load reduction and the possibility to obtain large deformations are the main advantages that can be reported during this forming process. Recorded forces necessary for material deformation are much smaller than during conventional forging process. High smoothness of the sample surface, material economy, simple design and easily exchangeable tools are also advantages of the forming technology. Unfortunately, some surface deformation may occur in front of the moving upper die, what may cause a micro crack initiation, especially for hardly deformable materials. The most popular simulation method of rotary forging is again based on the FEM approach (Nowak et al., 2008; Nam et al., 2014).

To overcome limitations of this process a new incremental technology was proposed for materials that are considered as hardly deformable (Grosman et al., 2012a). This new process is based on small incremental deformations realized by a series of thin anvils pressed into the material by rolls moving towards them. The subsequent accumulation of these small deformations finally results in the expected deformation. As a consequence, the pressure is not applied by the upper die directly to the material, but is transferred through series of thin anvils as seen in figure 19.

Thus, a reduction of necessary loads for plastic deformation is visible, as well as reduction of total energy required to obtain expected level of accumulated equivalent strain value. Also large deformation degrees can be obtained during cold forming without the need of additional heat treatment operations. This process joins advantages of orbital forging connected with multi point sheet forming. Typical applications of the process are ring forgings and ribbed wheels. It is also possible to manufacture products with small thickness, deep indentations or with wide surfaces with additional stiffening ribbing. Development of this process was closely supported by s series of numerical simulations realized within the finite element framework e.g. (Grosman et al., 2012a; Grosman et al., 2012b).

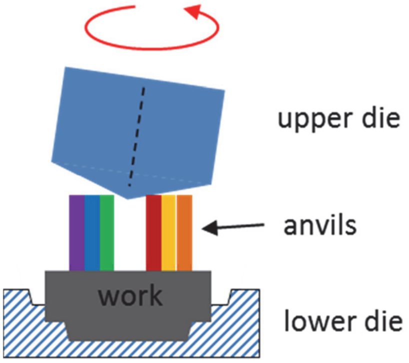

Fig. 19. Schematic illustration of modified orbital forming process.

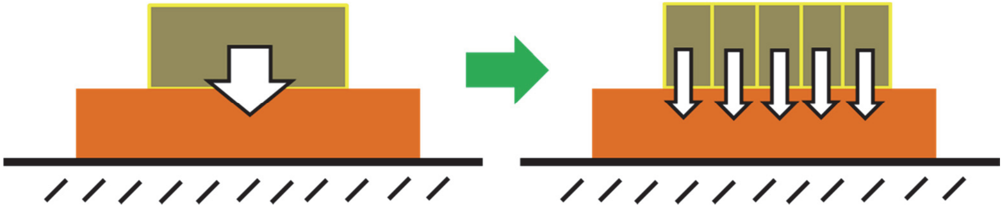

Fig. 20. Idea of an incremental forming approach.

As presented, the latter technology is the only good alternative that can be used to manufacture integral elements. However, the method is limited only to cylindrical shapes of products. The solution may be recently proposed modification (Grosman et al., 2012b) of the technology that can be applied to manufacture different shapes of final products.

5. UNIVERSAL INCREMENTAL FORGING PROCESS FOR INTEGRAL ELEMENTS

The process of incremental forging proposed in (Grosman et al., 2012b) is a good alternative to described earlier methods of manufacturing integral elements. Excessive loads recorded on the presses during e.g. conventional forging are eliminated in the approach by division the one die into a series of small anvils that realize complex deformation in a sequential manner as seen in figure 20 (Grosman et al., 2012a). For these reasons, widely available presses, with lower press loads, can be used to obtain integral elements. What is more, incremental forming process, enables to obtain complex constructional elements during one process, without additional montage operations. Such technology can also be successfully used to manufacture products from materials that are considered as a hardly deformable (Grosman et al., 2012a).

The proposed idea for obtaining 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 especially useful in the aerospace industry. Schematic illustration of the technology is presented in figure 21.

Therefore, development of an innovative incremental forming process seems to be the best solution to obtain integral elements. However, to successfully apply this innovative forming technology at the industrial scale, engineers have to gain detailed knowledge on mechanisms that control deformation and microstructure evolution during complex deformation conditions occurring during the incremental process.

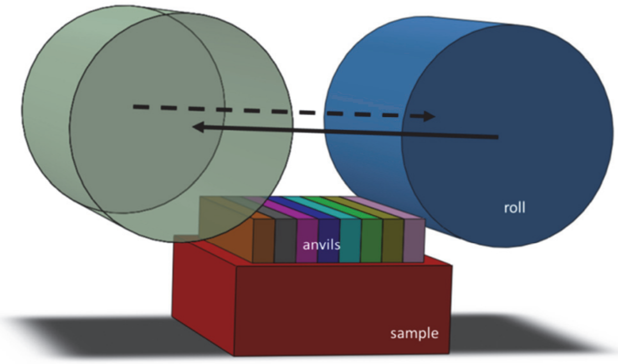

Fig. 21. Illustration of novel incremental forming process.

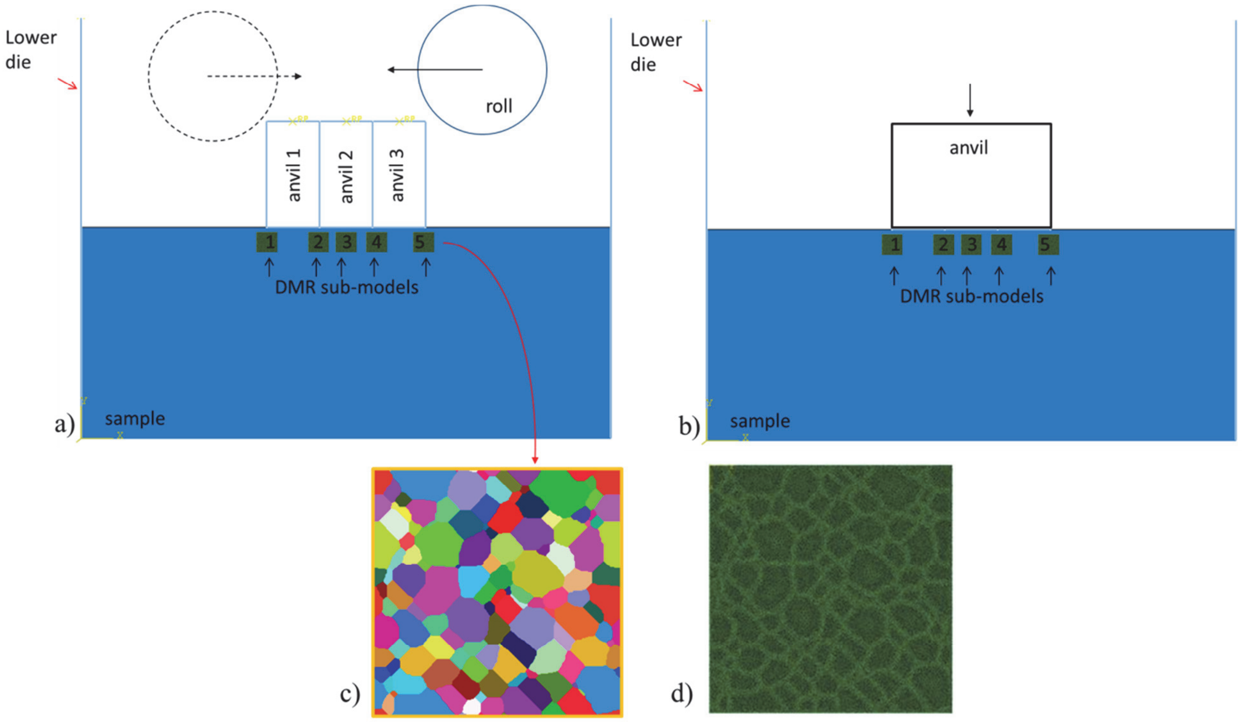

Fig. 22. *Illustration of the multiscale numerical model of a) incremental forming with 3 anvils and moving roll, b) conventional forging with one die, c) DMR model with 100 grains, d) finite element mesh generated with the DMRmesh software (Madej et al., 2012).*

Unfortunately, experimental research is 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. In the case of mentioned innovative incremental forming technologies, local inhomogenous material behavior at the level of subsequent grains cannot be neglected. Thus, to support development of the innovative process for obtaining light and durable integral elements, the multi-scale numerical analysis of this process is proposed, based on the Digital Material Representation (DMR) concept (Madej et al., 2014).

6. MULTISCALE NUMERICAL MODEL OF THE NOVEL INCREMENTAL FORGING PROCESS

As mentioned, the main motivation of this work, is development of the multiscale numerical model capable to replicate material behavior during the incremental forging technology not only at the macroscale but also at microscale level. Such model can provide basic knowledge on influence of process conditions (e.g. temperature, deformation degree, press velocity, die dimensions) on material flow directly under and on both sides of subsequent anvils. That way, effect of strain path changes in regions of material located between anvils can be evaluated. What is more, this analysis is supported by a microscale investigation of material behavior at the level of particular grains. That way information about changes in crystallographic orientation and texture inhomogeneities will be analyzed. Thus, the goal is a fully multiscale investigation realized to provide detailed understanding and knowledge on material behavior under incremental deformation conditions. This basic knowledge on material flow under the incremental deformation will be used in the future to properly design the manufacturing technology of mentioned integral components used in the aerospace industry.

To address mentioned goals, during preliminary work, a simplified version of the incremental forging method was proposed. Developed numerical model consists of only three anvils pressed by the moving roll into the material 0.2 mm 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 × 20 mm and 5 × 10 mm, respectively. A commercially pure aluminum material flow stress model, which is described by the Hansel-Spittel equation, was used during the investigation:

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

where: σ – flow stress; ε – equivalent strain; $\dot{\varepsilon}$ – equivalent strain rate; T - temperature in ˚C; model coefficients: A = 157.1988568, m_1 = -0.002015579, m_2 = 0.23768978, m_3 = 0.032042529, m_4 = 0.00023694.

process should be done using micro scale models located in these areas as seen in figures 25 and 26.

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.

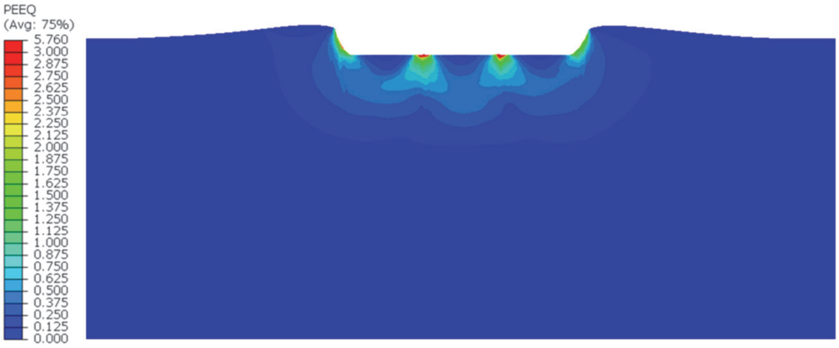

Fig. 23. *Strain distribution at the macro scale after incremental forging on 0.8mm depth.*

Fig. 24. *Strain distribution at a macro scale after conventional forging on 0.8mm depth (scale is shown in figure 23).*

The model was evaluated on the basis of the performed plastometric tests and inverse analysis (Szyndler & Madej, 2015).

Additionally, five micro scale DMR models containing 100 grains are attached in various interesting locations selected in the macro scale finite element model (figure 22). Both incremental and conventional forging processes where modeled to highlight differences between them. The data transfer between scales is realized by an interpolation of displacement boundary conditions from the macro to micro scale models.

Obtained results in the form of strain distributions for macro and micro scales are presented in figures 23-26.

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 three smaller anvils. Given results indicate that more detailed analysis of material flow in incremental forming Shapes of the first and the last DMR models 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 result 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. Also more elongated shapes of deformed grains can be seen after IF process in the zones between anvils (micro model no. 2 and 4). In the micro model no. 3, located directly under the anvil such behavior is not seen, and grains after deformation maintain its shapes. Contrary, conventional forging process shows different material behavior when forming with one large die is investigated. Obtained strain distributions across

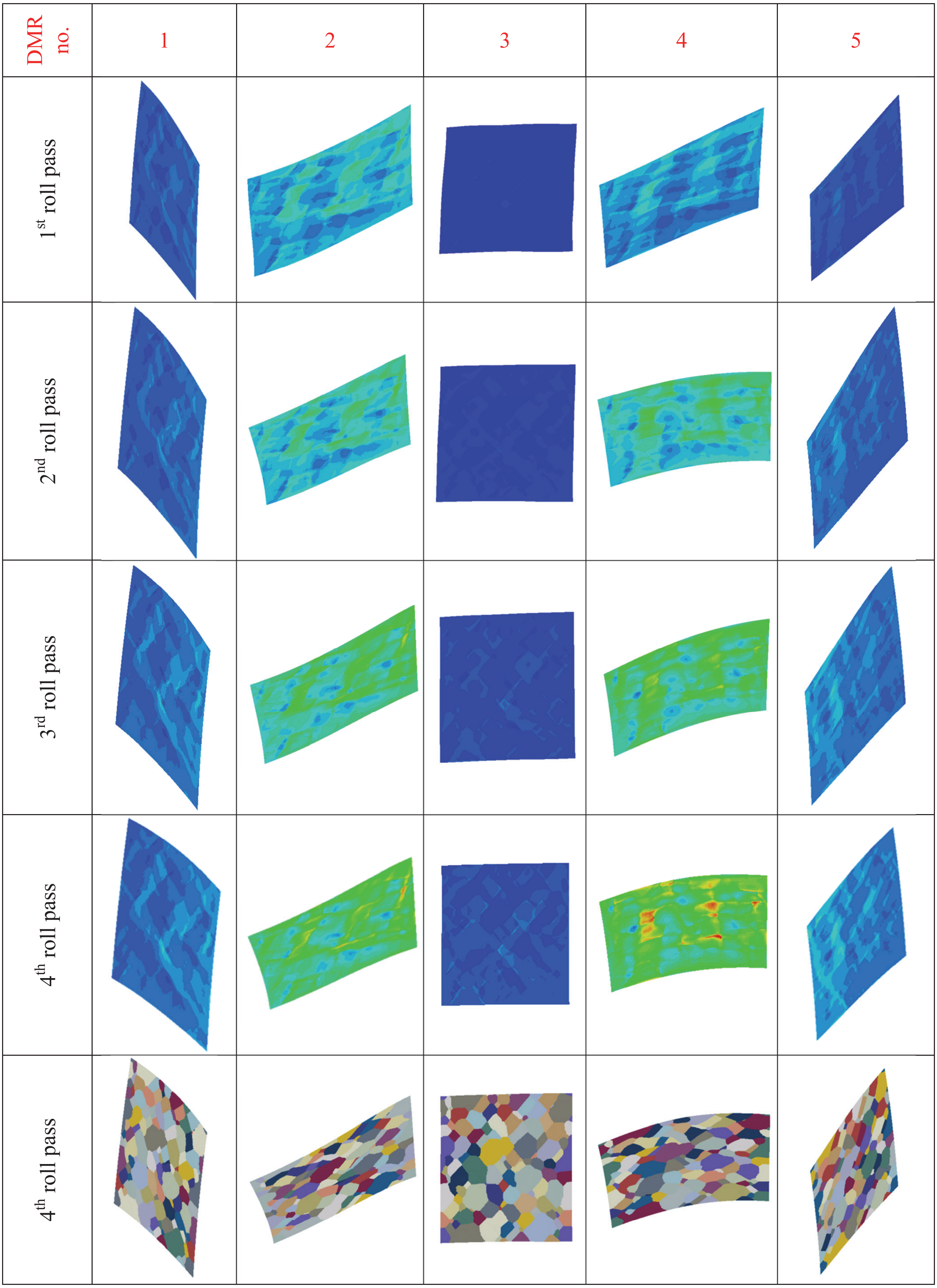

Fig. 26. *Comparison of strain distribution obtained every roll pass during incremental forming process and grain shapes after the deformation.*

microstructures located under the anvil are stable and values are very low. The strain localizes only in narrow zones at the corners of the die. Comparison between loads recorded in the incremental and conventional forming for the same process conditions is presented in figure 27.

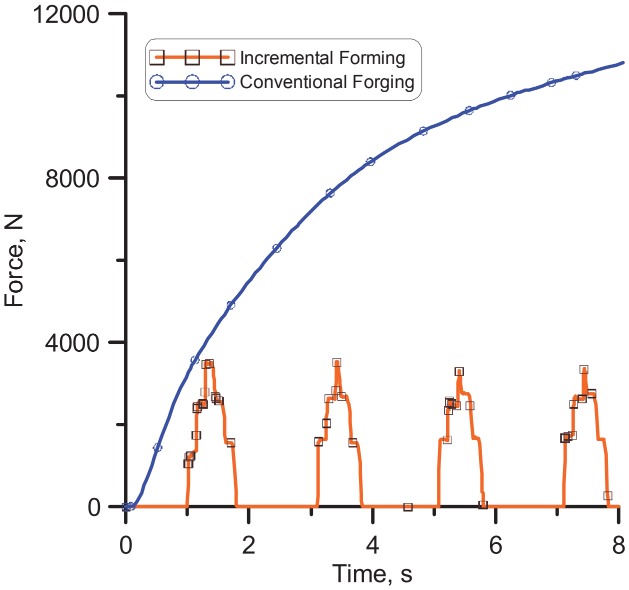

Fig. 27. *Press loads recorded during the simulation of incremental forming and conventional forging process.*

Comparison of loads presented in figure 27, clearly highlights the main advantage of the new process – reduction in loads required for material deformation. During the incremental forming, maximum recorded load is 2.5 times lower than in the conventional forming. It is expected that this reduction will be even higher when smaller diameter of working roll or higher number of anvils 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 (Szyndler et al., 2015).

7. SUMMARY

Detailed analysis of different forming methods of light and durable integral elements dedicated for the aerospace industry was presented in the paper. Description of an integral parts concept and basis of conventional processes for obtaining these parts were shown in detail. Wide range of manufacturing operations were presented and their advantages and disadvantages were pointed. The first part of the paper can be summarized as follows:

- Machining is the oldest and most frequently used method of obtaining integral elements for the aerospace industry, however from economical point of view it is costly as large quantities of material are wasted in the form of scrap.
- Machining is an effective way of finishing treatment for elements that are obtained from other manufacturing methods.
- The fastest and easiest way of forming integral elements characterized by stiffening ribs is a shape rolling. Unfortunately, this method has some application limitations caused by difficulties with obtaining expected height and thickness of stiffening ribs.
- Extrusion is an effective manufacturing method, but mainly used at elevated temperatures to reduce excessive loads during forming. The method gives good quality of semi-finished products and also is a good solution from economical point of view.
- It seems that the best properties of integral elements can be obtained by pressing/forging methods. These forming methods have wide range of possibilities to control mechanical properties of obtained parts. The limiting factor of pressing/forging of integral elements is that they are connected with excessive press loads, which are necessary to obtain parts with required dimensions. The solution to the problem may be modified incremental forming method based on e.g. orbital forging.
- From economical point of view, casting is the best way to obtain parts with complex shapes and wide dimensions in quite short time. Unfortunately, a lot of practical experience is needed because of problems with obtaining thin-walled elements and with shrinkage phenomenon.
- Large flexibility in obtaining complex shapes of integral elements is also attributed to chemical pickling process. However, the main disadvantage is necessity of providing appropriate safety measures, more complicated than during machining or metalforming operations.

The second part of the paper describes innovative concept for obtaining diversified shapes of integral parts from aluminum alloys based on incremental forming with division of one die into a series of small anvils. As mentioned, such a solution can minimize loads used during forging. Special consideration was put on computer aided support of development of that incremental forming technology. Based on this part of the research it can be summarized that:

- Developed multiscale model indicates that during the incremental forming process recorded loads are much lower than during conventional forging. It is expected that the more anvils will be used, the higher difference between recorded loads during incremental and conventional forging will be visible.

- During IF strain values accumulates near sample surface, under anvils, what in consequence can improve strength properties in this part of obtained elements.
- The DMR concept provides detailed information on local micro scale behavior, and indicates that the strain path change effect can occur during the deformation. That will be carefully investigated in further work.

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METODY FORMOWANIA ELEMENTÓW DEDYKOWANYCH DLA PRZEMYSŁU LOTNICZEGO

Streszczenie

Celem pracy jest szczegółowa analiza różnych metod przeznaczonych do formowania lekkich i wytrzymałych elementów integralnych, dedykowanych dla przemysłu lotniczego. Zaprezentowano koncepcję elementów integralnych oraz podstawy konwencjonalnych procesów technologicznych stosowanych do ich kształtowania. Następnie opisano procesy kształtowania przyrostowego z podziałem na kształtowanie blach oraz elementów objętościowych. W pracy przedyskutowano również obecny stan wiedzy w tym zakresie zarówno od strony badań laboratoryjnych jak i analizy numerycznej. Ostatecznie, przedstawiono nową koncepcję alternatywnego procesu kształtowania przyrostowego dedykowanego dla uzyskiwania elementów integralnych ze stopów metali lekkich. Szczególną uwagę poświęcono wsparciu opracowywanej innowacyjnej technologii formowania od strony wielkoskalowych symulacji numerycznych.

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