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CONCURRENT ENGINEERING BASED ON VIRTUAL MANUFACTURING

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Original scientific paper
The paper deals with the concurrent engineering concept that implies simultaneous activities in integrated product and process development, through the application of Virtual Engineering Technologies, especially in the simulation of production, i.e. Virtual Manufacturing. The main goal is to minimize design modifications in final design stages, and therewith time and costs of design of product and related processes. Expensive physical prototypes and experiments can be avoided by applying numerical FE/FV simulations. Development time is drastically decreased; many design alternatives can be verified, leading to quality improvements. Application of CE concept is illustrated through numerous case studies of numerical simulations of processes using SIMUFACT.forming software: thick sheet forming, forging, net-shape forming, hot profile extrusion, etc.

Keywords: concurrent engineering, FE/FV simulations, virtual manufacturing

Simultano inženjerstvo utemeljeno na virtualnoj proizvodnji

Izvorni znanstveni članak
U radu je razmatran koncept konkurentnog inženjeringa koji podrazumijeva simultane aktivnosti u integriranom razvoju proizvoda i procesa, kroz primjenu inovativnih tehnologija virtualnog inženjeringa, posebno u dijelu simulacije proizvodnje, tzv. virtualne proizvodnje. Cilj je da se minimiziraju projektne izmjene u kasnijim fazama projektiranja, a time i vrijeme i troškovi projektiranja proizvoda i pripadajućih procesa. Primjena FE/FV simulacija može eliminirati skupe fizičke prototipove i eksperimente. Vrijeme razvoja se drastično smanjuje, više projektnih alternativa se može provjeriti, što rezultira povećanjem kvalitete. Primjena koncepta ilustrirana je brojnim primjerima numeričkih simulacija proizvodnih procesa korišćenjem SIMUFACT.forming softvera: oblikovanje debljih limova, kovanje, "net-shape" obrada, toplo istiskivanje profila, itd.

Ključne reči: *simultano inženjerstvo, FE/FV simulacije, virtualna proizvodnja*

1 Introduction

In recent years, industrial companies are under lot of pressure, because they have to satisfy customers' requirements and to stay competitive on the international market. Nowadays, we have market trends such as: increasing international competitiveness, shorter product life cycle, requirements for high quality and high reliability of delivery. Besides, technological development and innovations offer new possibilities for application of innovative VE (Virtual Engineering) tools, new strategies in product and process development. Companies' capacity to apply and adjust advanced technologies in product development and manufacturing is essential on today's dynamic global market.

It is estimated that 80 % of a product's price is determined in the early stage of its life cycle, so companies are impelled to seek the ways for fast decision making in the process of its design, which is directed towards the issues of price, quality and requirements of the market. The main objective of engineering design is to develop and manufacture products that are optimized in terms of quality and reliability, in the shortest time possible and with minimum price. The ideal design process needed to achieve this objective must work in the environment for virtual product development, where designers, technologists, engineers from shop-floor, even suppliers of both components and services, cooperate with one another and have quick access to updated design information.

The virtual engineering technologies have many advantages and possibilities in innovative product and process development, realized in the computer environment with the aim to model, simulate and optimize the product. However, individually none of them is sufficient to satisfy high requirements and goals of engineering design. Necessity of technological integration of VE technologies is imperative, specially having in mind the complexity and required flexibility of products on the market. If we consider the complexity of engineering design in the automotive industry, where typical car can have 3000 ÷ 5000 parts and most of them must work in different models and assembly configurations, we can conclude that it is impossible to answer the market requirements by developing such complex products through expensive and time consuming physical prototypes. The process of development, design and manufacturing of complex products, without the complete integration of VE technologies, raises several key issues in business management, such as [1]:

- increase of costs, time and failures – missing connection of data from CAD system, with virtual product model, and decision making in business and revision of product design increase the mentioned categories;
- poor product quality – design errors, resulting from inability to simulate performances of all product concepts and configurations, lead to the problems in quality and maintenance of a product;
- high maintenance costs – due to inadequate simulation of product performances in the early design stage, quality of product manufacturing and maintenance is jeopardized.

Integrated VE solution provides consolidated environment for modelling, analysis and simulation of products and production process, and also prevents the loss of information and electronic data, which is very often during their transfer. It allows easy transfer of data from different systems, from their design to analysis and control, and provides solid ground for virtual engineering based on simulations. Besides, virtual environment provides designers and engineers with product visualization and better understanding of the process, leading to improvement of quality and shorter time-to-market and providing adequate design solution which does not need expensive redesign later on.

2 Concurrent engineering

Concurrent engineering is a business strategy which substitutes the traditional product and process design with an approach where different tasks are realized simultaneously and adequate attention is paid to all aspects of product and process development at the very beginning. Such strategy is directed towards optimization and distribution of company's resources in the field of design and development, with the aim of providing effective and efficient product and process development.

Companies often apply concurrent engineering approach at least at some point of the manufacturing process, without actually defining it as such. Several different terms can refer to the same principles, such as simultaneous engineering, integrated product and process design, concurrent design, etc. and they are all applied practically. The original definition which is very often cited was first introduced in 1986 by the Institute for Defense Analysis (Institute for Defense Analysis, Report R-338): "The concurrent engineering is a systematic approach to the integrated concurrent product design and related processes, including manufacturing and assembling. Such approach is designed to integrate all aspects from the beginning of the product development, i.e. to consider all elements of product life cycle, from the origin of an idea to the product disposal, including quality, expenditures, planned time and customers' requirements."

Since this definition, many others have been published. Most of them are focused on integration and management of process design with the aim of achieving shorter time-to-market. Various definitions that can be found in the literature cover a large range of concepts, from teams' management to cutting the costs. Here is the list of some characteristics describing design process with the application of the concurrent engineering [2]:

- focus on users and their involvement in the process;
- involvement of suppliers in the early stage of design and continuous cooperation;
- multi-disciplinary teams with stronger powers;
- joint use of information with constant increase of knowledge;
- focus on the product life cycle;
- systematic and integrated approach;
- concurrent (simultaneous) design teams;
- application of tools for DFX design in the early stage;
- application of modern tools such as CAD, CAM, CAE, finite element method, etc.;
- continuous improvement of all processes in design.

If we observe the difference between sequential and concurrent engineering, first we have reduction of design modifications in concurrent engineering, exactly as the consequence of involvement of all those parameters related to the product life cycle in development process and product design, from the very beginning. Having that in mind, questions related to the maintenance, manufacturing and customers' use of products are considered in the early stage of the design process due to engagement of multi-disciplinary teams. Consequently, the total time of development is significantly reduced as well. Typical decrease in time by applying concurrent engineering compared to sequential engineering is shown in Fig. 1.

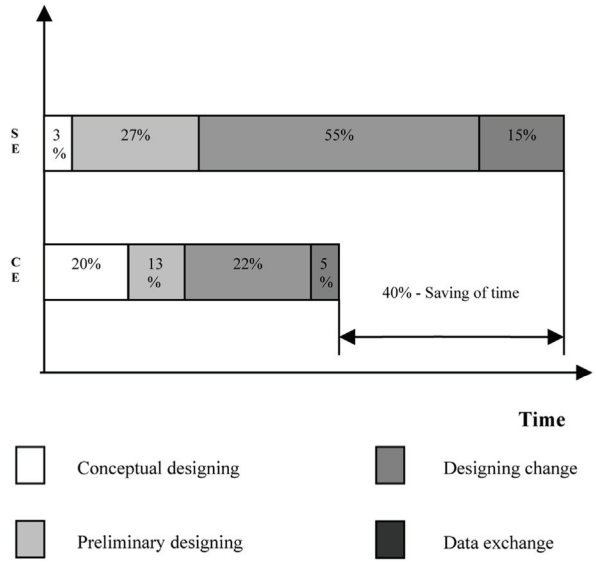

Figure 1 Presentation of time savings in the application of concurrent engineering (CE) compared to sequential engineering (SE) [3]

3 Virtual manufacturing

The application of numerical simulations is a verified and extremely useful tool for predicting the problems in the industrial manufacturing and reducing the time and costs in the development of new products. Expensive tool prototypes and multiple corrections can be found in the traditional "trial-and-error" design process. Although it is based on vast experience of experts from industry, such approach cannot satisfy the companies' need to develop new concurrent products for global market quickly and efficiently. The mentioned concept of concurrent engineering implies simultaneous execution of project activities, so VM technologies are widely applied in the areas of engineering analyses of products and processes, in the early stage of conceptual design. Exactly those VM technologies are based on non-linear FE analysis of engineering problems and as such they are applied in virtual integrated products and process design [4, 5]. Their basic advantage is the possibility of "what-if" simulations, enabling the designers to estimate various design alternatives on the virtual process models, planned in the product design. It has already been emphasized that for the success of design, an early estimation of project alternatives and decrease in engineering changes in the early design stage are essential. Since virtual models of production processes are very flexible, they allow examination of design modifications effects, both product and tool geometry and process parameters, on the product quality and manufacturing costs. In such conditions, it is possible to optimize the design of both product and related processes, to predict the failure and defects on the product and to use optimally manufacturing equipment and tools, increasing their life time by reducing the wearing and preventing the fractures. Optimal choice of relevant manufacturing parameters has positive consequences on the manufacturing costs, costs of material and tools, final quality of the product and its life cycle.

Shorter time-to-market can be achieved by applying VM technologies, i.e. numerical simulations, in the early stage of design, before the tool manufacturing and test production, because all possible problems can be identified and avoided. This confirms the well-known saying: «an ounce of prevention is worth a pound of cure». Tools for numerical simulation of manufacturing processes are not only the support to the product development and optimization of manufacturing processes, but the tool for support to PLM system as well, for right decision-making by the management in the stage of design, because it allows:

- right choice of production technologies for product manufacturing
- right choice of materials for the product
- verification of tool geometry
- reducing the number of tool prototypes
- optimization of process parameters for specific production technologies
- right choice of manufacturing equipment through the estimation of forming loads.

The following part of this document presents case studies in application of virtual engineering technologies in product and process design, realized in the Centre for Virtual Manufacturing (CEVIP) at the Faculty of Engineering, University of Kragujevac, using software Simufact.forming [6, 7].

4 Case studies

Presented case studies as virtual manufacturing applications in different industrial process have been performed using special-purpose software Simufact.forming, as a consolidated version of its predecessors MSC.SuperForm and MSC.SuperForge. It is intended to 2D and 3D simulation of cold and hot forming processes, based on integrated FE (Finite Element) and FV (Finite Volume) technologies. It represents the combination of complex solver and simple user environment specially adjusted for 3D simulation of bulk forming. The method of finite volume is more rapid and precise because it does not apply remeshing and it is used for monitoring the material flow and automatic improvement of facets on the free model surfaces. Finite element method is also integrated into solver, with the option of automatic remeshing, for application in the more demanding applications and calculations of tool stress.

4.1 Thick metal sheet forming – springbacks

The bending belongs to the group of most frequently used methods within the plastic forming technologies. It allows production of a large range of products, with parts from 1 mm to several meters in size. In bending technology and tool design, elastic springback should be considered. The size of elastic springback depends on many factors such as: characteristics of workpiece material, thickness of metal sheet, bending radius, part shape, bending type, etc. Increase of the yield stress (R_p) and ratio of r/s with the decrease of metal sheet thickness leads to the increase of elastic springback. Reversibility does not occur only in metal sheet forming, but also in bending of bars, sticks and wires of any cross-section.

Analysing the geometry of workpiece (see Fig. 3) by applying available theoretical and semi-empirical equations, it was determined that reaching the radius r = 550 mm after the bending would be aggravated because all prerequisites leading to elastic springback existed. 2D FE process analysis was realized in characteristic cross-sections, labelled with 20 %, 28 % and 80 %, as shown in Fig. 4. The material of metal sheet was S235JRG2 (1.0038) (EN 10027-1) (old Č0361) ($R_{p0,2}$ = 240 MPa), and its thickness was 3 mm. The flow curve for this material is described by the following equation:

$$k = C \cdot \varphi^n = 677 \cdot \varphi^{0,168} \text{, MPa}$$

In analyzed cross-section, 1317 square FE elements of 1mm in size were generated using Advancing Front Quad mesher. Upper die stroke was 75 mm.

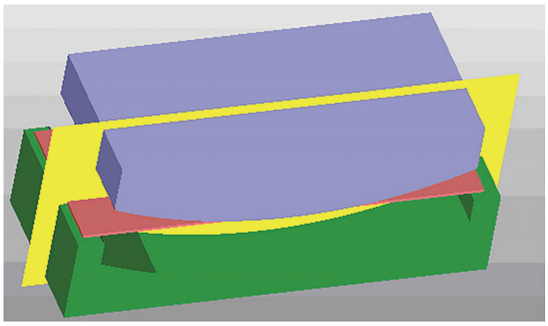

Figure 2 Tools and sheet workpiece set-up and cross-section for 2D FE analysis of springback

Tab. 1 shows comparative results of FE analysis and industrial part measurement on CMM. In Fig. 3, we have visually presented piece after the bending and springback, obtained by FE simulation. The difference in FE and measured values of the workpiece was less than 0,2 mm.

Table 1 Comparative displacement values in the direction of x and z axis after elastic springback, in mm

Position of cross-section	Displacement along the z-axis (FE)	Depth of the piece (FE)	Workpiece expanding along the x-axis (FE)	Displacement along the z-axis (CMM)
20 %	10,695	49,305	6,29	10,87
28 %	10,605	49,395	6,72	10,56
80 %	10,325	49,675	6,03	10,36

Correspondence of generated results suggests the possibility and reliability of FE analysis of similar forming processes of thicker metal sheet in the initial design of technology and tools. There on the virtual models we can predict effects of elastic springback and thus carry out optimization of process and tool geometry before actual production and test manufacturing.

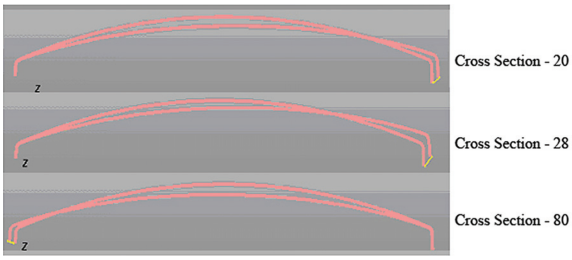

Figure 3 Workpiece before and after spingbacks

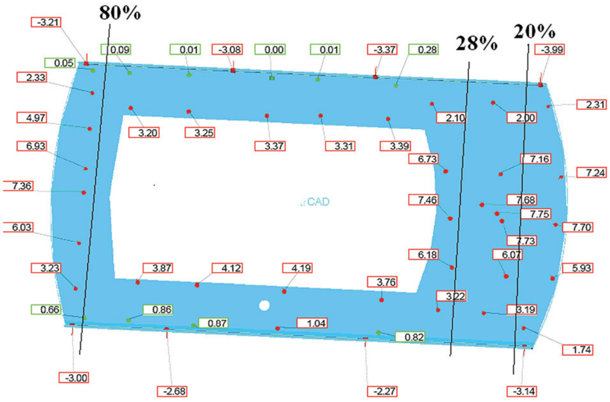

Figure 4 CMM measuring card of workpiece after springback

4.2 Porthole-die extrusion of Al profile

Hot porthole-die extrusion of aluminium alloys for the production of hollow profiles has many advantages in comparison to conventional approach, which includes application of additional elements in the exit part of die. Heated preform runs through the tool container and when it reaches the portholes, it leads to its splitting and plastic flow through the cavities on the matrix. Afterwards, inside the chamber separate parts of preform are welded up so that on its way out of the die, the profile with internal hole can be formed.

Tool design for this kind of process is very complex and strongly depends on the designers' experience. Only a well-designed tool can produce desired profile accuracy and satisfying tool firmness. However, in the early stage of tools design like this, there are many unknown issues, so the designers themselves cannot be absolutely sure about the adequacy of the design solution before the testing. Shop floor try-outs lead to significant expenses, because of both interference with current manufacturing and necessary changes on the tool.

The aim of the realized research was to determine the quality of welded zone during the extrusion of Al profiles, applying FV process simulation. Initially, examination was carried out on the preliminary design solution of tool and with process parameters defined by the manufacturer himself. In further researches, variation of tool geometry, temperature and material type were carried out in order to obtain more favourable pressure in the welding chamber, as well as better quality of welded surface.

Input data for FV analysis and simulation of process are: profile material AlMgSi0,5 (AA6060), tool material X38 CrMo V5-1 (1.2343) (VDHe) (old Č4751) (H13), tool temperature 420 °C, billet temperature 480 °C, billet size ∅157 × 400 mm, friction factor m = 0,6, forming speed 0,333 m/s (hydraulic press).

Fig. 5 shows the values of pressure in the cross-section of extruded profile and part of formed material in the welding chamber. Unequal distribution of output velocity of extruded profile, shown in Fig. 6, leads to bending of extruded profile, but only at the beginning of the process. This is also confirmed by industrial experiment – the front part of the extruded profile (Fig. 7).

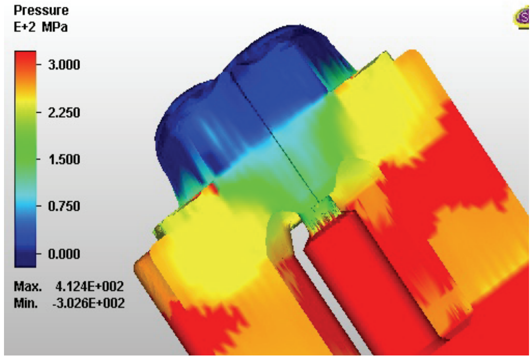

Figure 5 Distribution of pressures in the welding chamber

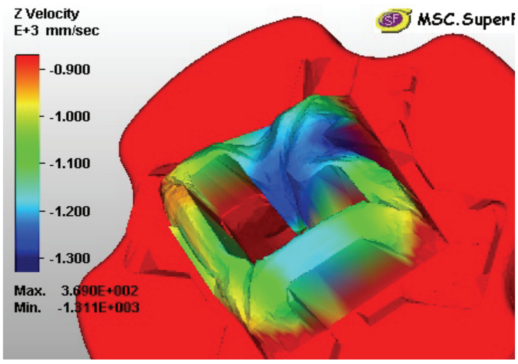

Figure 6 Distribution of output velocity in the extrusion direction

Figure 7 Industrial experiment

During the extrusion of the profile with small wall thickness, excessive pressures can occur in the welding chamber and tool components that form inner cavity in the profile. For simulation of hot extrusion of Al profile with 1 mm of wall thickness, all process conditions, profile and tool materials are the same as in the previous example. Such processes are very demanding for numerical simulation. Application of finite volume methods provides significantly reduced CPU time and successful simulation of complex material flow.

Fig. 8 shows the results of process simulation by applying Simufact.forming v8.1 software, with new Simlab mesher integrated, that allows automated so-called swap-remesh type of local facets. Initial size of facet was 1 mm, but during the simulation, especially in the zones of extruded profile, it was decreased completely automatically (when needed). Application of Work mesher gives poor performances of local refinement of facets, as presented in Fig. 9. Distribution of pressures in Fig. 10 shows maximum pressures on the central part of the tool which forms the inner cavity, as well as the bridges of the porthole-die.

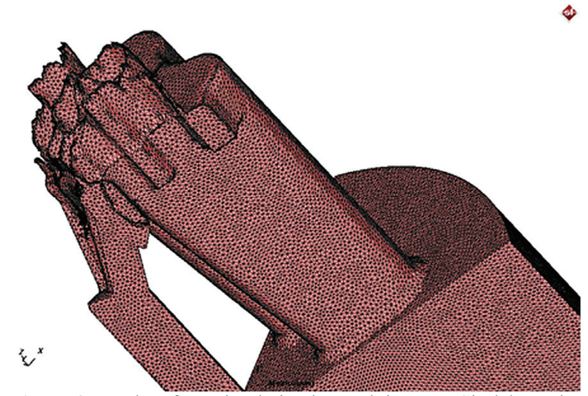

Figure 8 Results of FV simulation by applying new Simlab mesher

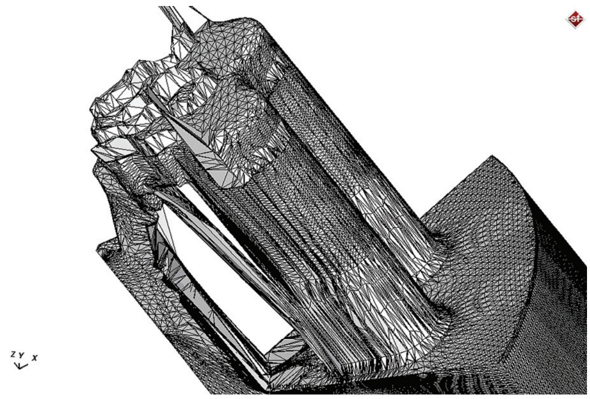

Figure 9 Results of FV simulation by applying Work mesher

4.3 Hot forging

Hot forging of aluminium alloys with increased hardness (AlMgSi1) is used for obtaining the parts of very precise dimensions, quality of surface, with minimum requirements for additional processing, that are expected to have increased exploitation capabilities, e.g. in automotive and aerospace industry. The development of precise forging, based on traditional hot forging, allows the production of complicated forging elements with fibre structure that follows the outline of the forging, quality microstructures and corresponding mechanical characteristics and dimensional tolerance.

The main problem with forging Al-alloys is the need for precise maintaining of the piece temperature, significantly affected by strain-rate. Temperature intervals of forging are small and must be respected. In presented example, additional problem was existence of folds during the forming of adjacent surfaces that are under angle of 90° in the forging part. Temperature regimes of processing are as following: before forging the tool was heated to the temperature of 250 °C, and workpiece was heated to the forging temperature of 470 °C.

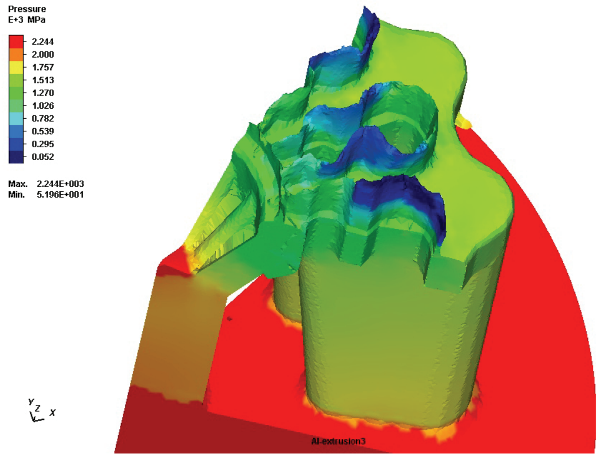

Figure 10 Distribution of pressures during the extrusion process

Fig. 11 presents the temperature distribution in the forging part, whereas Fig. 12 shows identified folds on its lower side.

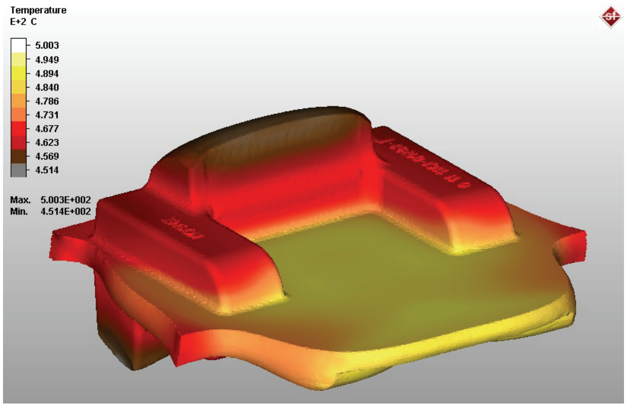

Figure 11 Distribution of temperature in the forging part

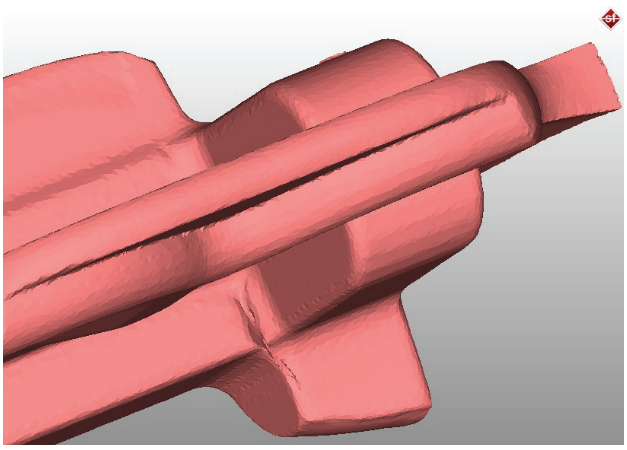

Figure 12 Folds on the lower part of the forging

Forging simulation of the fork forging showed that there was the problem with filling the tool, and thus the dimensional inaccuracy of the forging part. Simufact.forming software allows the contrast preview of workpiece with red zones which is in contact with the tool during the forging and blue zones that do not have any contacts (Fig. 13). In that way, it is easy to identify the areas where the tool is not filled and to take some corrective measures of tool redesign before its real manufacturing. Virtual models are flexible for modification of tool geometry, process parameters and other significant factors, so it is possible to carry out the process optimization. FV estimation of material flow was consistent with industrial process (see Fig. 14).

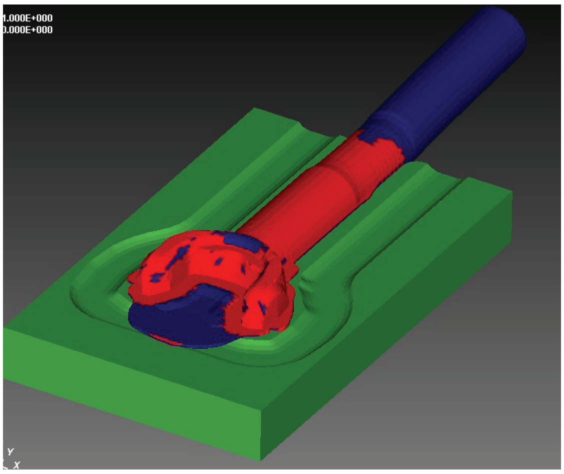

Figure 13 Zones where tool is not filled (blue)

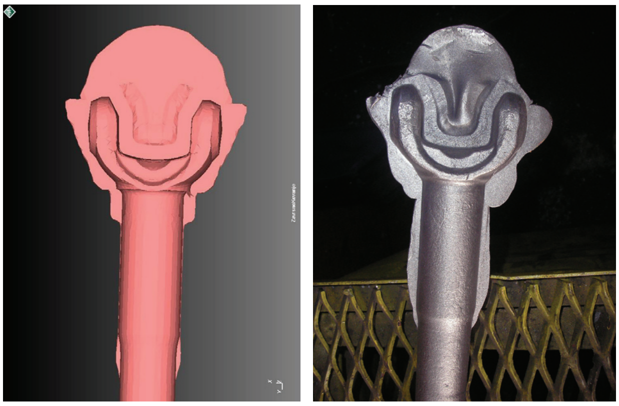

Figure 14 Comparison of virtual model and forging part

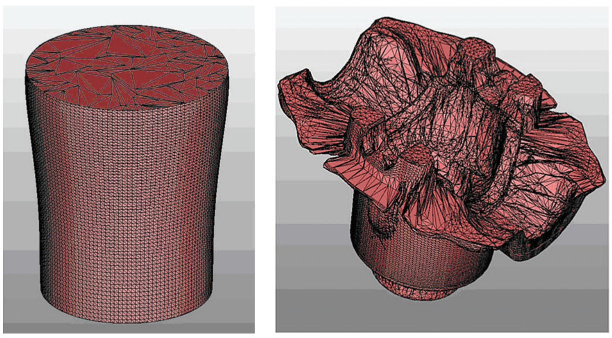

Figure 15 Upsetting and previous forming stages

Additionally, by applying numerical simulations it is possible to assess the forming load of the process, discover the critical zones of excessive stress, which can lead to premature tool wear and eventually to fractures. In the example of three-stage forging, shown in Fig. 15, the tool broke in the stage of previous forging, at the punch stroke of 77 mm (F = 9310 kN). When the stroke was changed to 67 mm in the previous operation, the load was F = 9516 kN, and the forging part completely filled the tool for the final forging as we can see in contrast presentation in Fig. 16. Blue zones exist only in the area of flesh that is part of forging for trimming.

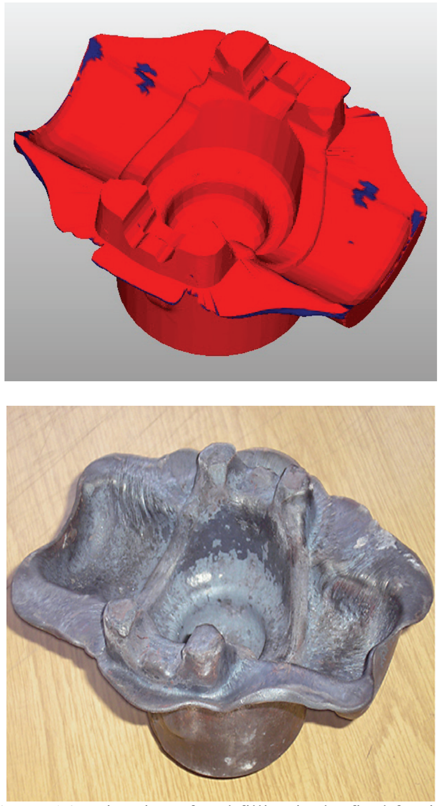

Figure 16 Estimation of tool filling in the final forging

4.4 Net-shape forming

Production of finalized parts in cold multi-stage forming processes, so-called net-shape forming is today widely applied in the manufacturing of gear parts, having in mind the surface quality and dimensional accuracy of workpiece, as well as avoiding additional processing through cutting. In these processes of cold plastic forming, tools bear large pressures and very often do not have economical life cycle. Having in mind that maximum permissible die stresses are up to 2500 MPa, reinforcement rings are used and in that way die can be prestressed immediately before the forming. In practice, die reinforcement is based on the experience, without detailed analysis, so the tool's life cycle can be significantly shorter than expected.

The simulation of processes such as these and tool analysis are not simple at all, because apart from the elastic-plastic analysis of tools and complex contact conditions, at the same time "alive" forming of workpiece in the tool has to be monitored. Simufact.forming supports this coupled analysis of plastic flow of workpiece material and simultaneous structure analysis of whole set of tools.

In this paper, this is illustrated on the process of cold extrusion in three stages, where the first and second ones are backward extrusions and the third one is combined extrusion for the forming of inner gearing at the bottom of workpiece. The workpiece material is 17Cr3 (VDEh, EN 10027-1) (old Č4120), punch and die are made of S 6-5-2 (VDEh) (old Č7680) (63 HRC), and reinforcement rings from steel 56NiCrMoV7 (VDEh) (old Č5742).

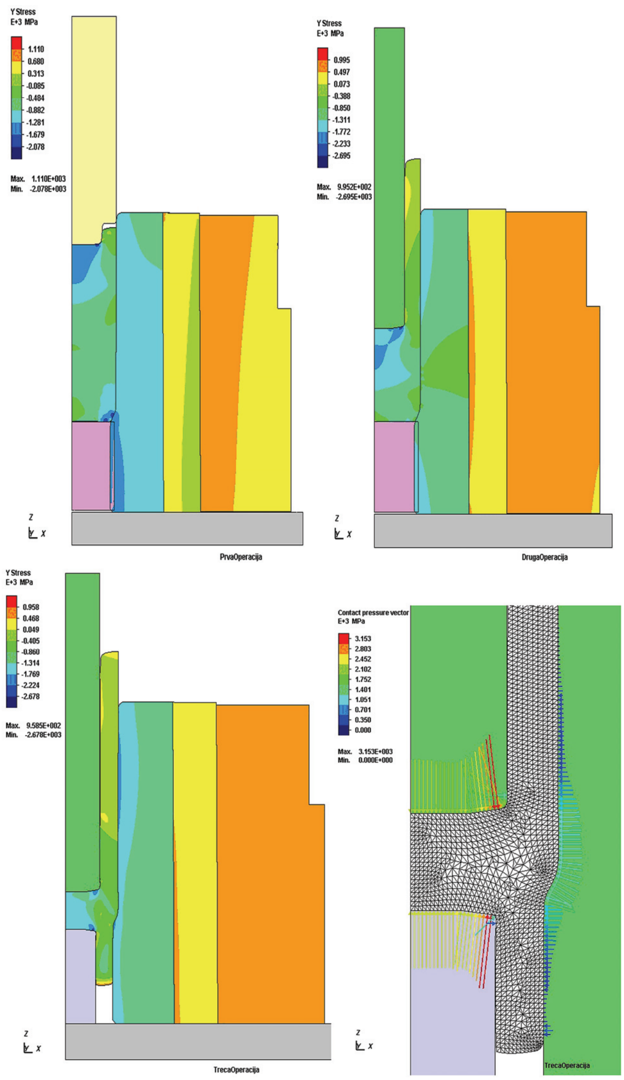

Figure 17 Stress fields in workpiece and tool, contact pressures

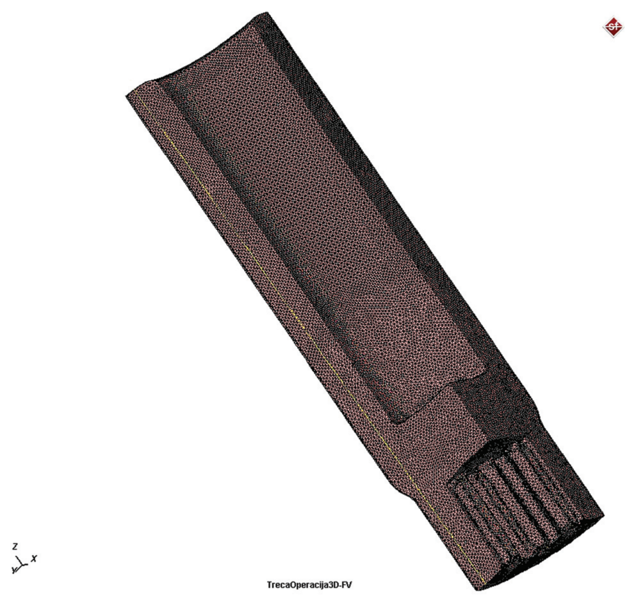

Figure 18 Virtual model of workpiece after the third stage of combined extrusion

Negative clearance in assembling the rings onto the die was 0,57 and 0,38 mm. The contact friction was assigned with the friction factor of 0,12 (phosphatized surface and lubricated). In such conditions, stress distribution of the reinforced die and rings was obtained. During simulation of forming process, coupled analysis was performed, workpiece forming and elastic deflection of die and all rings. Fig. 17 shows some of the results of realized researches.

Except the stress analysis of the tools, it is very useful to estimate the dimensional accuracy of workpiece as well, which is conditioned by elastic stress of the matrix, and additionally by the conditions of contact friction, especially in the case of "divided" material flow in combined extrusion. In Fig. 18, the virtual model of workpicece at the end of the third extrusion stage, with characteristic measures is presented.

5 Conclusion

The virtual engineering technologies are a very powerful tool in the stage of conceptual product design and development and assessment of different solutions for corresponding technological processes, as a prerequisite for the application of the concurrent engineering concept. All design alternatives can be verified and all possible errors and defects can be identified in short time and with minimum costs, because the modifications are made on the virtual models of the process. Besides, the optimization of the product manufacturing and/or its component, but also of the tool itself and its life cycle, leads to drastic improvement of product quality and the reduction of manufacturing and maintenance costs, which has positive effects on competitive position of an enterprise.

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