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PHYSICAL MODELLING AND FEM SIMULATION OF THE HOT BULK FORMING PROCESSES

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ABSTRACT

The paper deals with problems of physical and numerical modelling of hot bulk processes, with plasticine as a model material. Usage of program for numerical simulation and physical modelling techniques are complementary, due to their advantages and restrictions. This way the results verification for both methods is done, which enables their application for real processes. Besides that, the problem visualisation and monitoring of the whole process in laboratory conditions, without stopping the actual production, enables the tool designer to significantly decrease costs, to increase tool life, to predict and prevent potential defects in material flow, to improve achievable tolerances and final part properties, to lower the tool wearing and to prevent its fatigue failures, to optimise the process parameters, to determine the forming load etc.

1. INTRODUCTION

Within the research and development of the bulk forming processes, the application of 2D/3D FEM program for numerical simulation of the process and physical modelling technique, with the application of modelling materials, are complementary. The application of C-technologies in all phases of process design and in designing and manufacture of tools is very popular at the moment. Numerical simulation of the process has numerous advantages, it is a powerful tool in the hands the explorer and the designer and it is often treated as the universal support system in solving of forming problems. However, the accuracy of the results of such simulation and their transfer onto the real processes depend highly upon the accuracy of input parameters of FEM analysis and boundary conditions, so the verification of the results is necessary. The best way of verification is on real processes, but that can be slow and expensive and, sometimes, unfeasible. For that purpose, the method of physical modelling with application of softer modelling materials can be applied, whereat that is only one out of many reasons for the application of this method, which is getting more and more used round the world, both in leading world academic centres and in many companies which are involved in production and processing of metals. In some cases the numerical models provide more flexible analysis of material flow in bulk forming processes, because they allow faster changes of geometry and tools travel, as well as following of influence of those changes upon the output information of the numerical experiment. On the other hand, the physical models also help the designer by the visualisation of the problem in cases of complex 3D geometries, when it is impossible to carry out the numerical simulation or when calculations require a lot of time. The simultaneous application of both methods eliminates the individual limitations and disadvantages and offers the explorer and designer a lot of information on the process itself. Besides that, by the application of these methods the designer can reduce the production costs by providing the requested tolerances, by increasing the tool life, by predict and preventing the flow defects, and also by foreseeing the piece properties by FEM estimation of microstructure [8]. The application of these methods represents the new concept in designing of processes and tools, for which we shall use the abbreviation in this paper – PMNS concept (Physical modelling and numerical simulation).

The aims of PMNS concept in designing of processes and tools for bulk metal forming are:

1. Improvement of tools design and establish of process parameters by means of:
    - determining of material flow and of final piece dimensions,
    - detecting and prevention of flow defects,
    - simulation of processes, with the aim to verify the tools filling,
    - control of conditions of contact friction and heat transfer,
    - predict stresses in dies for preventing premature die failure and increase of tool life;
2. Improvement of part quality and reduction of manufacturing costs by means of:
    - determining of strain-stress-temperature fields in piece and tool,
    - predicting the microstructure and control of grain size,
    - decrease of unsuccessful attempts in production, of type "*trial and error*",
    - reducing of lead times,
    - reducting rejects, improvement of material flow.

The use of this new concept in designing of processes and tools has significantly increased, especially during the last five years, in research and development activities of the leading world centres, in academic institutions ([2], [13], [4], [3]...) and development laboratories of the companies ([12], [11]…). There are the numerous literature examples of the application of such concept in finding the optimal design solutions for the new products and improvement of the existing ones.

2. PHYSICAL MODELLING

The main idea of this method is the replacement of the real metal materials with soft model materials which have the similar behaviour during plastic forming, such as waxes and modelling clays, plasticine being the most distinguished among them. Review and characteristics of model materials which are used in physical modelling are given in the paper [6]. Due to the small flow stress of these materials, the modelling experiments can be performed in laboratories on smaller tools and devices which can be made of aluminium, wood, plexiglass, plastic masses etc. By the application of multicoloured models and tools with transparent front and modern equipment for data acquisition, the entire process can be recorded with the digital camera, thus obtaining the permanent record, the analysis of which gives a lot of information on the process itself.

Physical modelling of the process with the application of the model materials, has numerous advantages:

- it is possible to analyse the process on smaller devices and presses without disturbing the ongoing process;
- it is often possible to observe the "live" forming inside of the model through transparent tool surface;

- it is possible to obtain a lot of information on the influence of changes of parameters onto the process course;
- behaviour of modelling materials at plastic forming is very similar to the real materials;
- the possibility for determining the process forming force on the basis of conditions of dynamic similarity;
- study and comprehension of mechanism of some appearances, verification of theory;
- the optimal preform geometry of tool for forging can be determined in a short time;
- visualisation and demonstration of the process for educational purposes;
- detection of critical spots of strain intensity and exceeding pressures, thus simultaneously increasing the tool life;
- study of the process of manufacture of complex geometry pieces (3D problems), when the numerical simulation is impossible.

However, the physical modelling by the application of modelling materials has its limitations in application:

- only processes in which the compressive stresses dominate in the material are modelled;
- temperature effects, such as generating and transfer of heat, cannot be analysed;
- the preparation of multicoloured models for visualisation of the process demands a lot of time;
- classic measuring on the sample, e.g. mesh coordinate, is made more difficult because of the model softness;
- processes, such as deep drawing, cannot be studied by this method;
- it is necessary to invest in tools, devices and equipment for correct execution of the experiment.

The execution of the experiment with modelling materials in laboratory conditions must satisfy the special conditions in which the physical modelling is performed. These conditions are defined by the main physical modelling law, which is based on the law of similarity [10]. The application of the law on similarity in the metal forming processes indicates that in practice it is impossible to achieve the perfect similarity in forming of model and real piece, which includes geometrical, kinematic, dynamic, material and thermal similarity. It is especially difficult to satisfy the conditions of thermal similarity, which implies the conditions of generating and transfer of heat during forming. The approximation of similarity conditions depends both on the modelling material and on the kind of process which is being modelled. By generalisation of approximate similarity conditions in forming process modelling [1] the significant conditions of similarity of model and real process are obtained:

- Equality or similarity of flow stress σ for modelling and real material. The flow stress for various materials can be expressed in the function of strain or strain rate.
- Characteristics of plastic flow must be similar, i.e., the forming of material remains homogenous or the degree of non-homogeneity is similar for the model and real process, i.e. the material flow is kinematically similar.
- Entropy remains constant during forming, i.e. the heat losses in contact with tool are equal to generated heat due to strain and friction;
- Tools have the similar geometry;
- The conditions of contact friction are similar, whereat this is most often mistreated as the condition of use of same or similar lubricant. The conditions of friction do not only depend on the type of lubricant, but also on the characteristics of materials regarding its sensitivity to strain rate, tool surface condition and realised working pressures in the process. Therefore, it

is necessary to determine the relative conditions of friction for each material and kind of processing.

Regarding the physical modelling of some processes by the application of modelling materials, the satisfying of aforementioned conditions consists of the selection of adequate modelling material, which represents the critical and crucial step in the modelling itself, and of the selection of the proper lubricant for satisfying the conditions of contact friction.

2.1. Experimental equipment

For the needs of physical modelling of the processes, the device was made which is connected to the additional equipment intended for the acquisition of data and assembled on hydraulic press of type *Erichsen*. In its central part, the device has easily variable tool work elements and it enables the simulation of various processes of bulk forming. The paper includes the modelling of simple type bulk forming processes (forward, backward and combined axis-symmetrical extrusion, axis-symmetrical forging in open tools). The entire forming process is recorded through transparent front, with digital camera, in several phases. Figure 1 shows the experimental equipment which consists of: 1) Device for physical modelling with modelling materials; 2) Hydraulic press, type ERICHSEN; 3) Three-component piezoelectric dynamometer, type KISTLER 9265A1; 4) Three-channel amplifier, type KISTLER Ca-5001 with components type 5007; 5) force gauge distributor, type KISTLER 9257A; 6) Inductive gauge of travel, up to 100 mm; 7) AD converter, 16-channel, 12-bit, type PCI-2000 2M; 8) HOTINGER bridge; 9) PC processor; 10) Stand for digital camera.

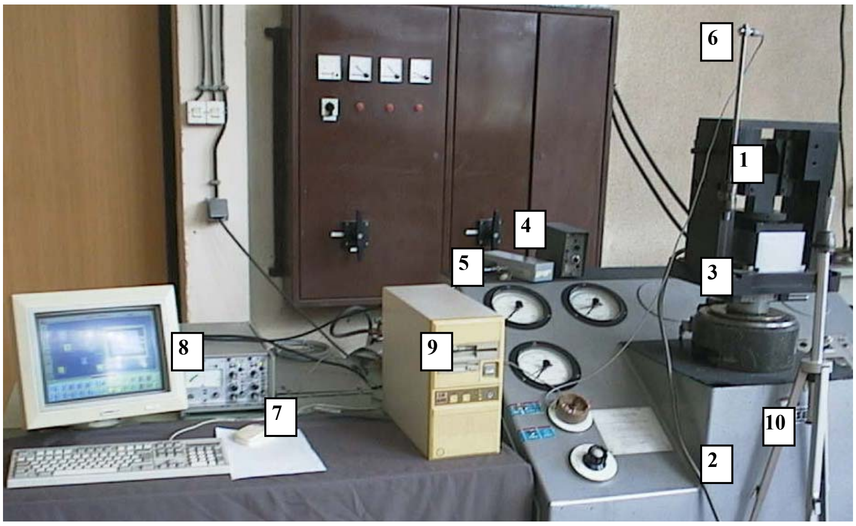


Figure 1 – Experimental equipment

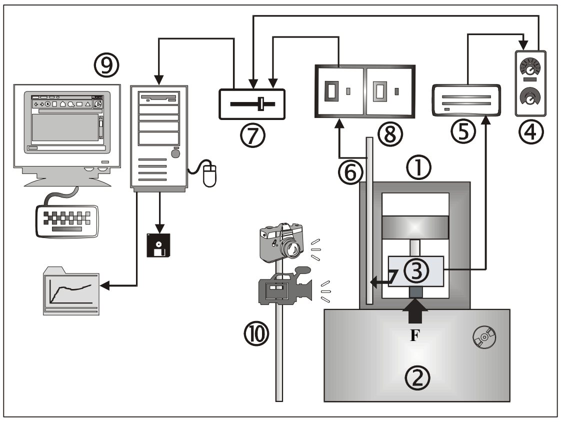


Figure 2–Device for physical modelling *Figure 3–Measuring chain of experimental equipment*

Figure 2 shows the device for modelling, with transparent tool surface front. Measuring chain of equipment is shown as scheme in figure 3. In the experiments of physical modelling, the forming load of the process is registered through piezoelectric gauge of force 3, and punch displacement is registered through the inductive gauge of displacement 6. The electric signals from the gauge are amplified in the amplifier of force 4 and Hotinger's bridge 6. After their digitalisation in AD converter 7, their acquisition and memorising on PC processor disk is performed. Processing of results, their control and process monitoring are supported by program package LABTECH CONTROL.

2.2. Selection of the model material

Diversity of real metal materials (pure metals and metal alloys) and also the diversity of cold and hot metal forming processes create the need for the development and application of as many model materials as possible, for the successful modelling of the process in various forming conditions. The crucial moment in physical modelling of the process is the selection of the adequate model material. During the many-year application of this method in solving of problems of forming, three main groups of modelling materials distinguished themselves: 1) Modelling clays (plasticine, mixtures based on plasticine and new modelling materials similar to plasticine); 2) Waxes (natural and artificial waxes, mixtures based on wax) and 3) Metals (lead, aluminium, sodium, tin, copper etc.)

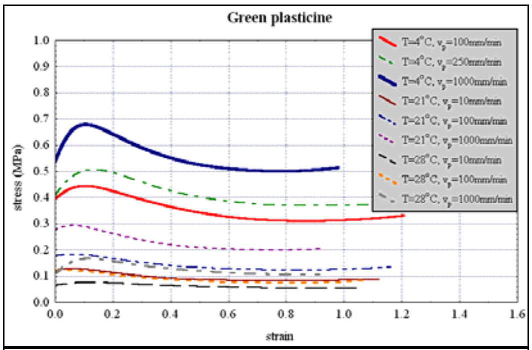
The approximate conditions of similarity, specified in the introductory part of the paper, in physical modelling by the application of model materials, consist of the selection of the adequate model material and similar conditions of contact friction. The expansion of these conditions, regarding the selection of modelling materials, would consist of the following demands which must be completely or partially satisfied by the good model, in dependence on the aims of modelling and kind of process [9]:

- The value of *Poisson*'s ratio ν must be equal for the model and real material;
- The ratio of tension strength and elasticity modulus R_m/E, or shear strength and shear modulus τ_m/G, must be equal for both materials;
- Equality of strain hardening coefficients n;
- Equality of strain rate sensitivity coefficients m;
- Elastic strains, which appeared in tool during the model shaping, must correspond to those in the real process.

Each model material has its advantages and disadvantages in the application, so there are no ideal model materials. The right selection is achieved by compromise, taking into consideration the characteristics and behaviour of material during forming, the determined aims of modelling, the kind of process and the available equipment, and the possibility to provide the new equipment.

In the experimental part of the paper, in the physical modelling of the hot bulk forming processes, pure plasticine and new model materials based on plasticine mixtures are used as modelling materials. With well planned and investigated influence of additives onto the material flow stress, the use of plasticine mixtures, as new modelling materials, offers the possibility for the obtaining the model material which has the similar flow curve as the real material, for which the forming process is modelled. At the Faculty of Mechanical Engineering in Kragujevac, the new modelling materials were developed, in the form of plasticine mixtures with smaller percentage shares of the following additives: kaolin, talc, paraffin, vaseline, and marble powder. Due to its viscose structure, vaseline, quite expectedly causes the softening of the plasticine and higher sensitivity to strain rate - temperature changes. Kaolin, marble and talc are in the form of powder, so they cause the strengthening of the mixture when added to plasticine. The plasticine which is used in this paper has the high percentage of grease and greasy acids in its structure, so the process of adding these powder materials represents the attempts to reduce the viscosity of the material and its strengthening. Paraffin, as an additive, has been used mainly in mixtures based on wax, causing the strengthening of the mixture. One plasticine mixture was obtained by adding paraffin, and, in that case, the changes of flow stress in dependence on influential factors were followed up.

For all model materials, base plasticine and it mixtures, the flow curves were determined by the compression test, at optimal lubrication of front surfaces of the cylindrical prepared parts with glycerine, which provides the forming conditions at approximately uniaxial compression. On the basis of well-conceived plan of multifactor experiment, the following was determined: flow stress in the function of strain, strain rate and temperature, at T=11, 21 and 28°C, and v_p=10, 100 and 1000 mm/min. Figure 4. shows the comparative diagram of the flow curves for the green plasticine, which was used for multi-layer plasticine models and the figure 6. for one of obtained plasticine mixtures M6, with talc, kaolin and paraffin as additives [9].



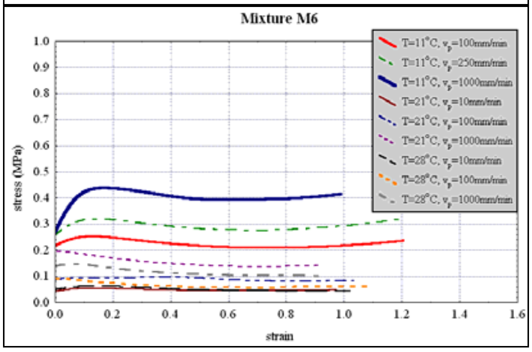


Figure 4 – Flow curves for green plasticine *Figure 5 – Flow curves for mixture M6*

By the regression analysis, with use of program package STATISTICA, the high-correlative mathematical models were obtained, with correlation factor higher than 0.987, for all modelling materials. For the green plasticine, the mathematical approximate model of flow is given with the equation 1, and for the mixture M6, with the equation 2.

$$\sigma = 0.022813\,\text{x}10^{-10}\,\varepsilon^{-0.18604}\,\dot{\varepsilon}^{0.18445}\,\exp(7397.41/T)\text{, MPa} \qquad (1)$$

$$\sigma = 0.048602\,\text{x}10^{-10}\,\varepsilon^{-0.08995}\,\dot{\varepsilon}^{0.24565}\,\exp(7122.53/T)\text{, MPa} \qquad (2)$$

2.3. Model of friction

During the simulation of the bulk forming processes, the conditions of contact friction continuously change throughout the process and represent the complex analytical problem, which makes difficult the obtaining of the reliable mathematical model of friction. The results of numerical simulation highly depend on the boundary conditions which, among other things, refer to the contact friction as well. Besides that, the crucial step in the physical simulation of the process is the selection of the adequate lubricant, with the aim to establish the conditions of similarity of real and model process and validity of the modelling results. It is well known that the experiments with modelling materials illustrate the behaviour of real materials in the forming processes very well, so it is completely understandable that the tribological mechanism in modelling experiments is similar and as complicated as in the real processes.

There are two ways to establish the good model of friction in physical modelling.

One way is to investigate the conditions of contact friction of real metal material in the conditions of process execution, which are defined with the following factors: tool material, lubricant, work-piece material, temperature, ram velocity etc. For the same process a series of experiments should be done with the model material, with more kinds of lubricants, which are expected to give the similar friction conditions. The combination metal-lubricant and model material-lubricant, which gives the same forming figure of flow, points to the existence of the same contact conditions and thus points to the proper selection of the modelling lubricant. The other way of selecting the lubricant is the quantitative determining of the coefficients/factors of friction by the application of one of the methods. The most applied are the methods of split flowing of material, *ring test* and *cigar test* methods. Fulfilment of the similarity condition of contact friction of real and modelling process implies the knowledge of friction coefficients/factors values in the real process. The proper lubricant for the modelling experiment is the lubricant which gives the same value of friction coefficient/factor as in the real process.

For the investigation of the contact conditions in the modelling experiments with plasticine, a series of tests of free ring compression (*ring test*) was done for various tool materials and various lubricants, according to the plan of multi-factor experiment [8]. Metal and glass surfaces were selected for the tool material, and talc, vaseline, glycerine and mixture (50% vaseline and 50% liquid soap) were used as lubricants. Figure 6. shows the calibration curves Wanheim-Danckert [5] and some experimental results.

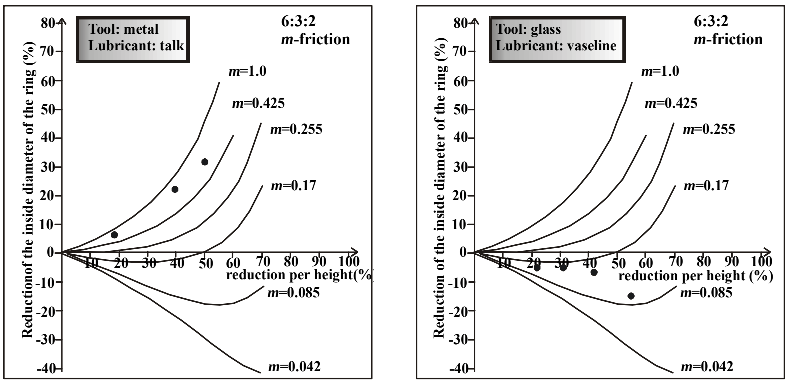


Figure 6 – Value of m- friction factor in modelling experiments with plasticine (ring test)

In the experiments of modelling of the process of hot extrusion and forging, talc was used as a lubricant (*m*=0.9). For contact surfaces of plasticine models and glass front sides of the device, vaseline was used as a lubricant (*m*=0.15), considering that in this way, the influence of friction in contact of meridian plane model and glass tool surface is minimised.

2.4. Experiments of physical modelling

Plasticine and its mixtures, the characteristics of which were described in the previous chapter, can be used only in the physical modelling of the hot bulk forming processes because of the prominent recrystallisation behaviour at plastic forming. Therefore, all the experiments of physical modelling and obtained results refer to the hot forming processes. In the paper, 2D processes of hot extrusion and forging with standard, simple geometries were investigated. All process models were selected at random and do not represent the models of actual industrial processes. That does not reduce the significance of performed researches, because the obtained results give a lot of information on the processes itself and represent the basis for the application of the new concept in design of industrial processes and tools, based on the simultaneous physical-numerical modelling.

Axis-symmetrical cylindrical plasticine models were made as two-colour multi-layer, of initial dimensions Ø 59 x 42 (59)mm. All models were cut through, on the tool with wire, along the meridian plane, so that the entire forming process would be recorded in that plane, through the glass tool surface, in the modelling device. The device contains easily variable central tool elements, which are used in the modelling of the process of axis-symmetrical and plane-strain extrusion (forward, backward and combined). Figures 7 and 8 show the central parts of tools for extrusion.

Figure 7 – Die and inserts, for axis-symmetrical extrusion of semi-cylindrical prepared parts

Figure 8 – Punchs for backward, plane-strain and forward extrusion

For the modelling of the process of axis-symmetrical forging, the inserts shown in figure 9. were used.

Figure 9 – Tools for modelling of the process of axis-symmetrical forging

Figure 10. shows the digital recordings of the plasticine models during the process of axis-symmetrical extrusion and forging. All shown models are deformed at ram velocity v_p=10mm/min and temperature T=21°C. During the experiment, the forming loads of processes and punch

displacements are registered through the gauge of force and displacement, and the permanent recording is obtained through AD converter and PC processor.

3. NUMERICAL FEM SIMULATION

The most applied and the most powerful "tool" for the numerical simulation of the forming process is certainly the finite elements method – FEM. During the last ten years, due to the rapid development of computer technique, many commercial program packages were developed on the basis of the finite elements method, for the solving of problems in metal forming processes. The user's interface is continuously being improved with aim of larger applicability in industry. The most popular program packages for the simulation of various kinds of bulk metal forming (forging, rolling, cold and hot extrusion, drawing, casting…) are DEFORM, FORGE, Qform, CAMPform, EESY-FORM, MARC AUTOFORGE… [4].

The possibilities and prices of these programs are various, in dependence on how much they are adjusted to the practical needs of the final user, through the user's interface, and how efficient they are in work regarding the accuracy of the analysis and computer time. One FE program will be applicable to the numerical simulation of the process, which is performed by the final user, if it satisfies the specific requests and if it has the additional programs for: a) interactive pre-processing, which provides easy entry of input data: geometry, characteristics of workpiece and tool material, boundary conditions and parameters for generation and regeneration of FE mesh; b) automatic generation mesh and remeshing; c) interactive post-processing for presentation of the results of FEM analysis.

In parallel with physical modelling of the process, the paper includes the execution of the numerical simulation in same conditions with the application of commercial software package CAMPform 2D. The program is intended for the simulation of 2D process by the finite elements method in PC environment. The program consists of solver, based on thermo-rigid-viscoplastic approach, and graphic user interface, which provides very easy entry of data on forming in pre-processing, and provides graphic information of simulation results in post-processing. The special advantage of program is the completely automatic generation of mesh at the beginning of the process simulation, and regeneration of the mesh, so called *remeshing* later, during the simulation, without any intervention of the user. According to the selection of the user, the output information are stress and strain components, strain rate components, forming load diagram, temperature distribution, ductile fracture in the workpiece, wear characteristics in dies etc.

Figure 10 also shows the numerical models, obtained by FEM simulation. The good congruence of figures of material flowing in physical and numerical models is evident. The aim of numerical CAMPform simulation of the extrusion and forging processes of plasticine models is the obtaining of similar numerical models, on the basis of which the application of FEM analysis would provide the obtaining of strain-stress-strain rate fields and other results of analysis, which would apply to both plasticine and numerical model types. The similarity of physical and numerical models is achieved with a few numerical experiments, with varying of FEM analysis parameters, and is tested qualitatively-visually. The absolute similarity of these models is not possible, because the numerical models are the product of the mathematical description of complex mechanisms of plastic flowing and tribological conditions. Even in the conditions of approximate similarity of physical and numerical models, the upcoming mistakes are smaller than they would be if the visioplasticity method were applied. In this way, by simultaneous physical-numerical modelling, even at approximate similarity of physical and numerical models, a lot of information on the forming process itself is obtained, with satisfactory accuracy of the results.

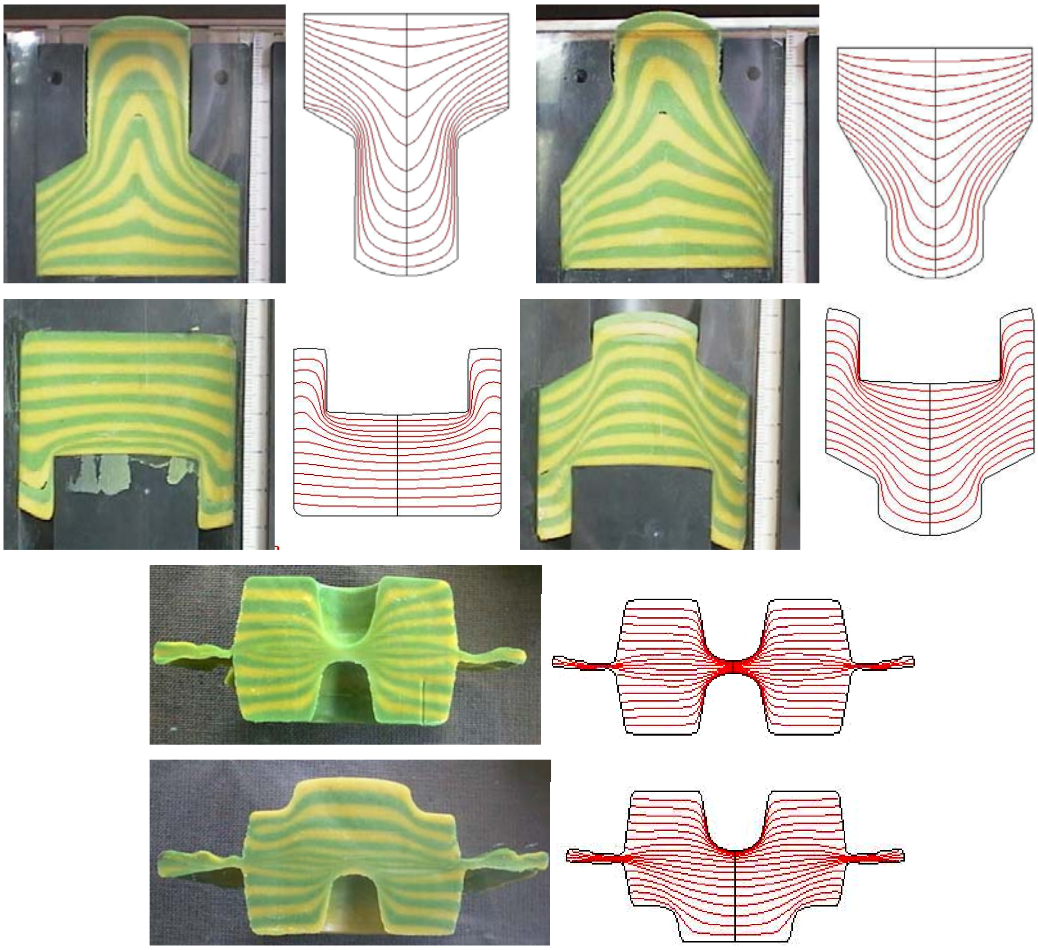


Figure 10 – Plasticine and numerical models

4. RESULTS OF PHYSICAL-NUMERICAL MODELLING

Considering the good congruence of models, the strain-stress analysis was executed only numerically, whereat the obtained distributions apply also to the physical plasticine models. Those are, in fact, the advantages of the new concept in design of tools for bulk forming. The whole process is modelled with physical models, and then the numerical FE simulation is executed for such models, with parameters which provide the congruence of physical and numerical models. Further strain-stress-temperature analysis is performed numerically. Here, only some of the results of the numerical simulation will be shown, as the illustration of the possibilities of CAMPform 2D program and advantages offered by numerical simulation of the processes.

Only some, out of many obtained results, are shown in the paper. Figure 11 shows the comparative diagram of forming load obtained with physical modelling and CAMPform simulation, for the case of forging of axis-symmetrical forged piece with plate. Figure 12 shows the distributions of axial components of strain and stress for the forged piece with plate, and the figure 13. shows the distribution of stress σ_{zz} and vector velocity field for the model of combined extrusion. Figure 14. shows the distribution of shearing strain and axial velocity, in the model of forward extrusion process through cone die, with central cone angle 120°.

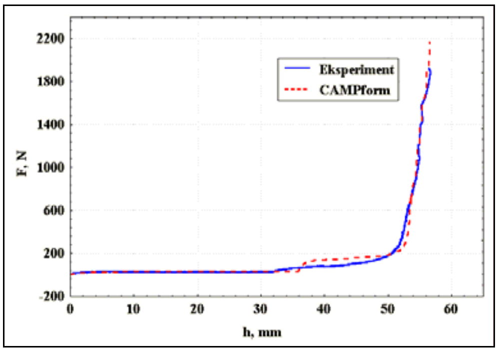


Figure 11 – Forming load diagram for forged piece

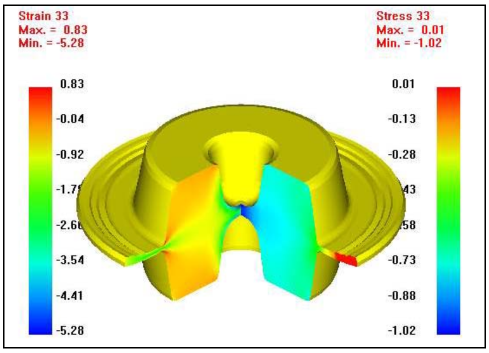
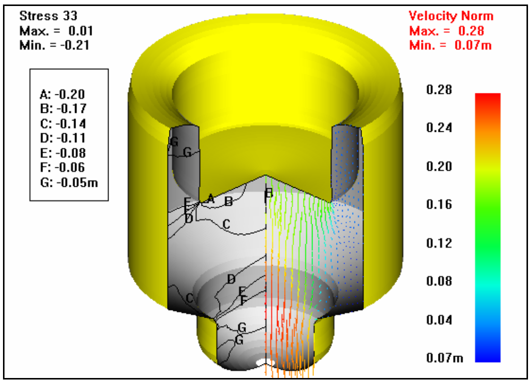


Figure 12 – Distribution ε_{zz} (left) and σ_{zz} (right)



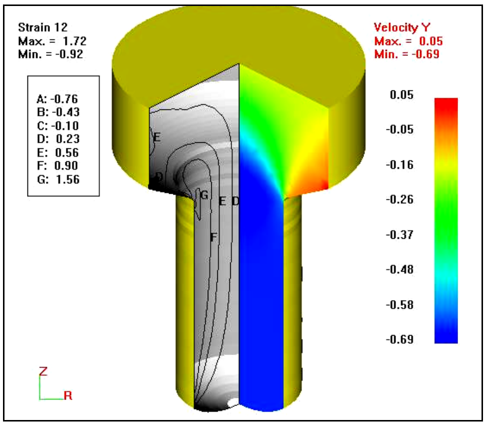


Figure 13–Distribution σ_{zz} (left) and veloc. vectors Figure 14–Distribut. ε_{xy} (left) and velocity v_y (right)

The shown results apply to the plasticine models and model processes. If the approximate conditions of similarity of model and real process are satisfied, then these results can be transferred to real forming processes. There are two ways of transfer of obtained modelling results [9]:

1. Numerical simulation of the real process, with analysis parameters determined in model processes, which provide the satisfactory similarity of plasticine and numerical models, but with given flow curve of real material and forming temperature. This means that the simulation is performed in conditions of real hot forming and forming force diagrams correspond to the real process force;
2. Execution of the dimension analysis and determining of proportion factor for the basic and derived physical quantities of model and real process [8].

5. CONCLUSION

The shown examples of physical modelling and numerical simulation of the standard processes of hot bulk forming indicate the advantages of such approach, and the possibilities of its application in the analysis of real processes and design of industrial tools. The efficiency of such concept is reflected through many advantages and possibilities offered to the designer and explorer:

- The development of new and improvement of the existing design solutions in the laboratory conditions,
- Application of inexpensive tools and devices, whose changes do not cause high expenses,
- Optimisation of designing of processes and tools,
- Visualisation of processes in cases of complex 3D processes,
- Understanding of the process physics and assessment of influence of process parameters,
- Inspection of tool filling and increasing of accuracy of part dimensions,
- Detection of critical spots of exceeding pressures,
- Detection of material flow defects,
- Analysis of tools wearing and elastic efforts, prevention of fractures,
- Determining of forming force of the process and energy necessary for forming,
- Increase of finished products quality by the FE evaluation of microstructure and grain size,
- Reduction of rejects and material loses etc.

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FIZIČKO MODELIRANJE I FEM SIMULACIJA TOPLOG ZAPREMINSKOG DEFORMISANJA

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REZIME

Rad obrađuje probleme fizičkog i numeričkog modeliranja toplog zapreminskog deformisanja koristećiplastelin kao modelni materijal. Korišćenje programa za numeričku simulaciju i fizičko modeliranje su komplementarni jer oba pristupa imaju i svojih prednosti i nedostataka. Na taj način verifikuju se rezultati istraživanja. Pored toga, vizuelizacija i monitoring procesa i laboratorijskim uslovima, bez prekidanja proizvodnje, omogućujući da se u procesu konstrukcije elemenata obradnog sistema postignu znatne uštede, poveća postojanost alata, spreče eventualna oštećenja alata kao i greške u tečenju materijala. Dalje prednosti su: poboljšanje tolerancija obratka, smanjenje habanja alata, optimizacija parametara procesa, određivanje energetskih parametara procesa itd.

U procesu fizičkog modeliranja korišćen je čisti plastelin kao i novo razvijeni materijal, baziran na mešavini plastelina. Ovaj materijal razvijen je na Mašinskom Fakultetu u Kragujevcu i ima niz prednosti u odnosu na postojeće modelne materijale.

Krive tečenja za oba primenjena modelna materijala su:

$$\sigma = 0.022813\,\mathrm{x}10^{-10}\,\varepsilon^{-0.18604}\,\dot{\varepsilon}^{0.18445}\,\exp(7397.41/\mathrm{T}),\ \mathrm{MPa}$$

$$\sigma = 0.048602\,\mathrm{x}10^{-10}\,\varepsilon^{-0.08995}\,\dot{\varepsilon}^{0.24565}\,\exp(7122.53/\mathrm{T}),\ \mathrm{MPa}$$

Problemu kontaktnog trenja kod modelnih materijala posvećena je posebna pažnja. Izvršena je serija testova sabijanja prstena kojim je određen faktor trenja "m" u različitim kombinacijama alat-materijal.

Modelovani su postupci istiskivanja. Materijal je podeljen po meridijalnoj ravni u kojoj je posmatrano odvijanje procesa deformisanja. Numerička simulacija procesa izvršena je pomoću FE programa CAMPform 2D.

Konstatovano je veoma dobro slaganje rezultata (napon, deformacija, sila).

Rezultati dobijeni na prikazani način mogu se, uz određene pretpostavke, primeniti i na realne procese (materijale) što je jedna od osnovnih prednosti ovog postupka.