UDK 519.61/.64:621.78:621.73.043
Professional article/Strokovni članek

ISSN 1580-2949
MTAEC9, 49(3)471(2015)

DEVELOPMENT OF NUMERICAL MODELS FOR THE HEAT-TREATMENT-PROCESS OPTIMISATION IN A CLOSED-DIE FORGING PRODUCTION

RAZVOJ NUMERIČNIH MODELOV ZA OPTIMIZACIJO POSTOPKA TOPLOTNE OBDELAVE PRI PROIZVODNJI ODKOVKOV V ZAPRTIH UTOPNIH ORODJIH

Ladislav Maleček[1], Mikuláš Fedorko[1], Filip Vančura[2], Hana Jirková[2], Bohuslav Mašek[2]

[1]COMTES FHT a.s., Průmyslová 995, 334 41 Dobřany, Czech Republic
[2]University of West Bohemia in Pilsen, Výzkumné centrum tvářecích technologií – FORTECH, Univerzitní 22, 306 14 Plzeň, Czech Republic
ladislav.malecek@comtesfht.cz

Prejem rokopisa – received: 2014-08-15; sprejem za objavo – accepted for publication: 2014-09-04

doi:10.17222/mit.2014.196

The paper describes a numerical simulation of the current technology of heat treatment of closed-die forgings made of the 25CrMoS4 steel. The aim of this simulation was to create a temperature model enabling a temperature analysis of closed-die forgings during the heating to the austenitization temperature. This model would permit the heating and soaking times to be reduced. The paper also describes a numerical simulation and material/technological modelling of the current forming technology and the subsequent still-air cooling of a selected type of closed-die forgings for the automotive industry. This numerical simulation provides information on the material flow, the part size and the deformation rate during forming and on the temperature conditions during handling, forming and subsequent still-air cooling. Using the material/technological modelling, samples corresponding to the selected locations of a forging can be obtained. By combining these two techniques, controlled cooling of closed-die steel forgings will be developed and optimized as a substitute for heat treatment. It is also possible to optimize the process in terms of both quality and energy consumption. Both numerical simulations were applied to the technology of forming and heat treatment of closed-die forgings of microalloyed steel, chromium-molybdenum 25CrMoS4, at the company of Kovárna VIVA a.s.

Keywords: 25CrMoS4, MARC, DEFORM, closed-die forging

Članek opisuje numerično simulacijo sedanje tehnologije toplotne obdelave odkovkov iz jekla 25CrMoS4 v zaprtih orodjih. Namen te simulacije je bil postavitev temperaturnega modela, ki bi omogočil temperaturno analizo odkovkov, kovanih v zaprtih utopih, med ogrevanjem na avstenitizacijo. Ta model naj bi omogočil skrajšanje ogrevanja in zadrževanja na temperaturi. Članek opisuje tudi numerično simulacijo in materialno-tehnološko modeliranje sedanje tehnologije preoblikovanja in ohlajanja na mirujočem zraku izbranih utopnih izkovkov za avtomobilsko industrijo. Ta numerična simulacija omogoča informacijo o toku materiala, o velikosti delov in hitrosti deformacije med kovanjem in o temperaturnih razmerah med manipuliranjem, preoblikovanjem in ohlajanjem na mirujočem zraku. Z materialno-tehnološkim modeliranjem se lahko dobijo vzorci, ki ustrezajo izbranemu položaju kovanja. S kombiniranjem teh dveh tehnik bo razvito in optimirano kontrolirano ohlajanje izkovkov v zaprtih utopih kot nadomestilo za toplotno obdelavo. Proces je mogoče optimirati tudi s stališča kvalitete in porabe energije. Obe numerični simulaciji sta bili uporabljeni pri tehnologiji preoblikovanja in toplotne obdelave izkovkov iz krom-molibdenovega mikrolegiranega jekla 25CrMoS4 v zaprtih utopnih orodjih v podjetju Kovárna VIVA, a. s.

Ključne besede: 25CrMoS4, MARC, DEFORM, zaprto utopno kovanje

1 INTRODUCTION

The production of closed-die steel forgings involves a series of forming operations and the subsequent heat treatment. The forming process typically consists of several operations. The ones most frequently used are upsetting, preforming, finish-forging and trimming. Trimmed forgings are transferred with a conveyor to a container where they cool down to the ambient temperature. In order to attain the desired mechanical properties, the cooling is followed by re-heating the concerned parts in a continuous-tunnel furnace and by quenching them. Today's closed-die-forging plants strive to shorten this cycle or even omit some of the operations.

Several approaches are available for achieving this goal. One of them involves the use of numerical simulations. The present paper focuses on two possible applications of a numerical simulation to optimise the production of closed-die forgings. The first one aims at optimising the heating and soaking of forged parts prior to quenching. The other uses a numerical simulation for constructing a material/technological model in order to develop a new method of the thermomechanical treatment of forged parts.

The goal of the first application was to construct a temperature model. It would be used for predicting the temperature fields in the forged parts during heating and soaking at the quenching temperature in the existing heat-treatment process. Knowing the temperature distribution, it is possible to adjust the process and potentially reduce the tact time in the production.

Table 1: Chemical composition of 25CrMoS4 steel in volume fractions, φ/%
Tabela 1: Kemijska sestava 25CrMoS4 jekla v prostorninskih deležih, φ/%

Element	C	Mn	Si max.	P max.	S	Cr max.	Mo max.
Content	0.22–0.29	0.60–0.90	0.40	0.035	0.02–0.04	0.90–1.20	0.15–0.30

With respect to the second application, the development of the material/technological model, the paper describes a comprehensive numerical simulation of a forming process, including the subsequent still-air cooling. The forged part in question belongs to a larger group of products of a similar shape. The paper also presents the results of physical modelling of the forging process on a thermomechanical simulator. It compares the properties of the resulting specimens with the conditions of the corresponding locations within the actual forged part.

2 NUMERICAL MODELLING OF HEAT TREATING A FORGED PART

The objective of the numerical simulation of the heat treatment was to map the effects of the radiant heat from the furnace lining on the forgings and the effects of the radiant heat between the forgings themselves. The forged parts were made of the 25CrMoS4 material (**Figure 1** and **Table 1**). In the process, these forgings were arranged in a charging basket passing through a continuous heating furnace.

The model was constructed with the use of the data obtained from the heat-treatment lines. The computation was carried out using the MSC.MARC/MENTAT software. This software employs the finite-element method and is suitable for solving multiphysical problems[1].

The simulation of the heat treatment was an iterative process. The goal was to fine-tune the simulation to match the data obtained from the heat-treatment lines. The iterative approach consisted of a gradual refinement and an addition of the input data to the computational model. The computational model comprised three types of bodies (groups of objects forming a single entity): the furnace, the charging basket and the forgings (**Figure 2**). The CAD models provided the input data for generating the mesh in individual bodies.

The meshes used for solving the problem consisted of hexagonal elements for the furnace and the basket and tetragonal elements for the complex-shaped forgings. The element size was changing in all the bodies as the computation was gradually made more accurate. There were two reasons for it. One was related to the total number of the elements and the other to the element size ratio with respect to the view-factor setting. The view factor is used in analysing the heat transfer by radiation. It defines the proportion of the radiation from surface A that reaches surface B. In the model, the view factor indicates the visibility of the face elements of the individual bodies in the furnace to one another and to the elements of the inner surface of the furnace chamber. As a rule, the more elements there are in a computational model, the more accurate the results are – and the more face surfaces of the elements there are. With these numbers increasing, the computation time of the furnace heating simulation increases as well. For this reason, the analysis was first tried out using a simplified thermal model shown in **Figure 3**. The goal was to examine the effect of the view factor on the heat transfer by radiation between two simplified objects.

The meshed objects were assigned material properties. The properties (the thermal conductivity and the specific heat) were measured for the forgings using thermophysical measurement methods. The material properties of the basket and the furnace were retrieved from the material data library of the software. The computation was fine-tuned by defining a permanent thermal contact between the basket and the forged parts. The

Figure 1: Shape of a forging – a 3D view
Slika 1: Oblika izkovka – 3D-pogled

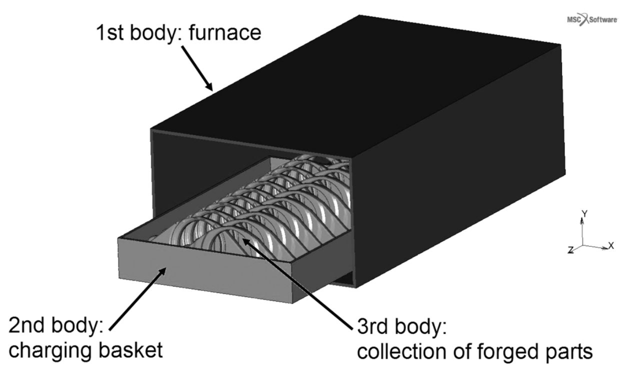

Figure 2: Bodies used in computing a temperature model in the MARC software environment
Slika 2: Telesa, uporabljena za izračun temperaturnega modela v okolju programske opreme MARC

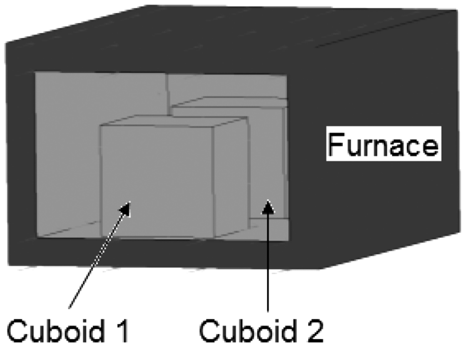

Figure 3: Trial model (examination of the effect of the view factor between two simple objects: cuboids)

Slika 3: Preizkusni model (preiskava vpliva faktorja videza med dvema enostavnima kvadratastima objektoma)

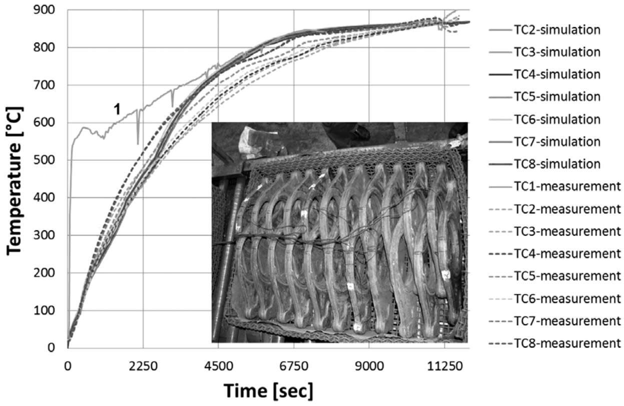

Figure 5: Comparison between the temperatures found with the numerical simulation and the field measurement (curve 1 shows the furnace temperature)

Slika 5: Primerjava med temperaturami, dobljenimi z numerično simulacijo in z meritvami (krivulja 1 prikazuje temperaturo peči)

initial temperature of the forgings was 20 °C. At the start of the simulation, the furnace temperature was 690 °C. It changed during the simulation in accordance with the schedule used. The furnace heating and soaking schedule was constructed in accordance with the real-world conditions. It was applied to the side walls and the top wall of the furnace chamber. Heating by radiation was first modelled using the MONTE-CARLO method which, however, did not yield adequate results. Therefore, the HEMI_CUBE method was employed. This method uses a pre-defined hollow space, within which the heat is reflected from or absorbed by the objects. The hollow space is a numerical zone where the outer elements of the bodies constitute a working space within which the view factor is computed.

Due to the increasing computation time, some aspects that substantially complicated the simulation were neglected and certain preconditions were defined. The variation in the position of the basket inside the furnace was neglected, as it can be taken into account by adjusting the thermal schedule. The wire basket was substituted with a solid metal-sheet container in order to shorten the computation of the view factor. The temperature field inside the furnace was considered to be uniform, although the actual temperature field is not constant. It is affected by opening the furnace door, by the transitions between its zones with different temperatures, the types of heating and the temperature-measurement methods. The results of the FEM simulation were compared with the temperature curves obtained in the selected locations of the real-world forgings in the production (**Figure 4**).

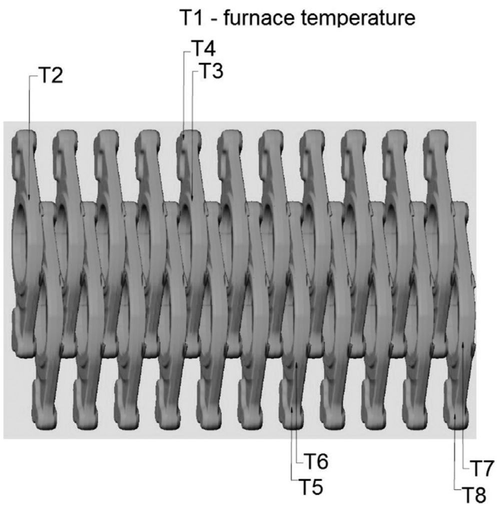

Figure 4: Layout of forged parts in the furnace with thermocouple locations. The layout was also used for the simulation of heat treatment (quenching).

Slika 4: Razporeditev izkovkov v peči s položajem termoelementov. Razporeditev je bila uporabljena tudi za simulacijo toplotne obdelave (kaljenja).

Simulation results (**Figure 5**) were in agreement with the temperature curves obtained for the forged parts in the continuous furnace. Therefore, the numerical model is suitable for this type of analysis. It can be used for predicting the temperatures of the forged parts during heating and soaking before quenching.

3 NUMERICAL SIMULATION OF FORMING AND COOLING A SPECIFIC TYPE OF FORGED PARTS

A numerical simulation of forging a selected type of forged part (**Figure 1**) was carried out using DEFORM 3D, a program developed for modelling forging processes. The input data for the simulation was obtained by measuring the mechanical and thermophysical properties of the 25CrMoS4 steel, the material of the forged part. The goal of the measurement was to obtain an accurate description of the plastic and temperature behaviours of the material for the numerical simulation. The plastic behaviour of the forged material was described with the flow stress/temperature (T), flow stress/strain (e) and flow stress/strain rate ($\dot{e}$) relationships in the form of curves. The flow-stress levels were found using the Rastegaev test[2,3]. The temperature behaviour of the workpiece, i.e. the changes in the temperature field within the

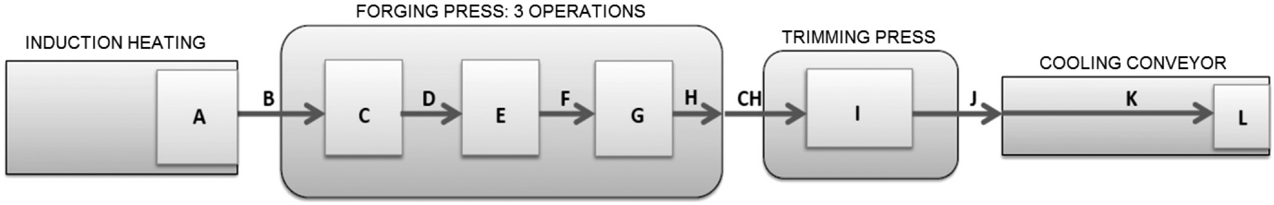

Figure 6: Block diagram of the manufacturing process of the forged part
Slika 6: Blok-diagram izdelavnega procesa izkovkov

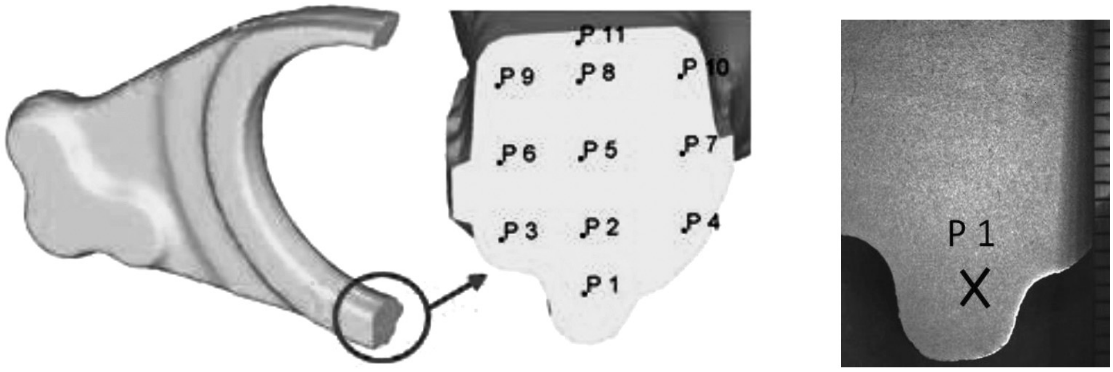

Figure 7: Tracked points on the cross-section of the FEM model of the forged part (left) and a micrograph of the P1 location on the real-world forged part (right)
Slika 7: Spremljane točke na prerezu FEM-modela izkovka (levo) in mikrostruktura položaja P1 v realnem izkovku (desno)

forged part during forming, was described using the measured specific-heat and thermal-conductivity values, as in the previous simulation of heat treatment. A kinematic model of the LMZ 2500 press, in which the actual forged part was made, was developed. The simulation was based on the forging-sequence description provided by the company of Kovárna VIVA a.s., as well as on the manufacturing-route analysis and on the field measurement (**Figure 6**).

The model comprised all the forming operations. Their sequence consisted of: upsetting – preforming – finish-forging – trimming. After the trimming, the forging cooled in still air to the ambient temperature. All the relevant handling times were taken into consideration, including the duration of the transfer of the forged part by the conveyor to the container.

The goal of the numerical modelling was to obtain the strain and temperature versus the time plots which were going to be used as the input data for the thermo-mechanical simulator (for the material/technological modelling). The material/technological modelling allows the entire process model to be validated using real specimens and also permits the microstructure evolution and mechanical properties to be mapped[4]. The point-tracking method was employed to determine the temperature-versus-time and strain-versus-time curves for the selected locations during the production of the forged part (**Figure 7**). A single representative point (P1) was selected for the physical simulation. The information obtained for this point of the forged part, i.e. the

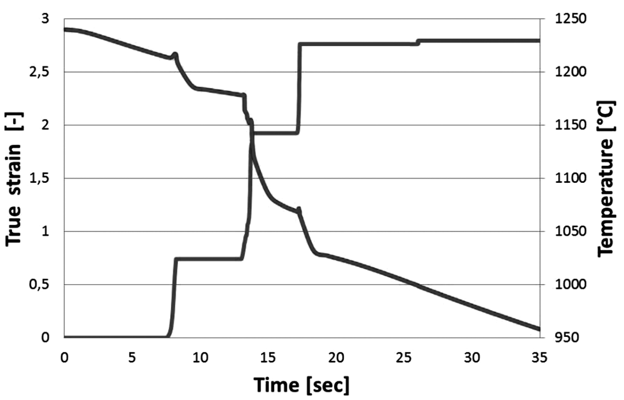

Figure 8: Strain and temperature plots for the tracked point
Slika 8: Diagram napetosti in temperature za preiskovano točko

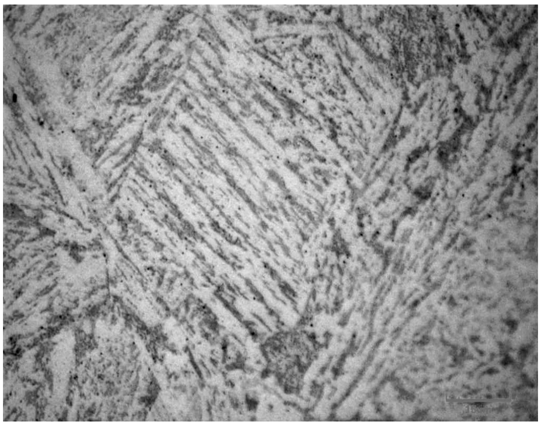

Figure 9: Bainite-ferrite microstructure of the forged part (HV 284)
Slika 9: Bainitno-feritna mikrostruktura izkovka (HV 284)

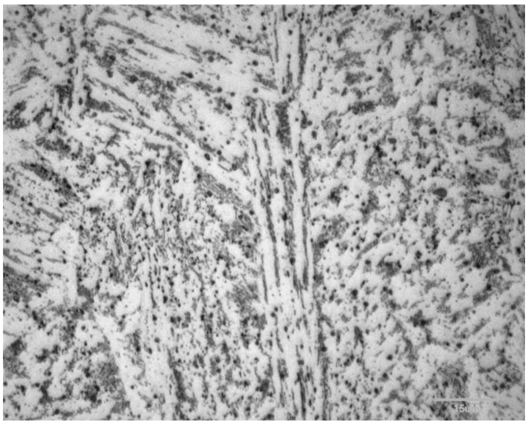

Figure 10: Bainite-ferrite microstructure of the physical-simulation specimen (HV 270)
Slika 10: Bainitno-feritna mikrostruktura v fizikalno simuliranem vzorcu (HV 270)

strain-time and temperature-time curves, is shown in **Figure 8**.

Using this data, a schedule for the thermomechanical simulator was developed and applied to an actual specimen. The microstructure of the real-world part (**Figure 9**) was then compared with the specimen microstructure upon the physical simulation (**Figure 10**) conducted for the selected point (P1). In both cases, the microstructure consisted of bainite and a portion of ferrite. For the sake of comparison, the measured Vickers-hardness values are shown as well.

4 CONCLUSIONS

Finite-element-method-based simulation is a powerful tool that can provide information about the variables that are difficult to measure otherwise: the strain and temperature curves for particular points of a forged part. The knowledge of these values is the key to optimising the existing processes and developing new procedures and materials. This is, however, impossible without verified models, required for a reliable analysis of the process. The present work deals with two applications of a FEM simulation to analysing the manufacturing routes in closed-die forging.

The first application of the numerical simulation involved constructing a temperature model. It described the temperature changes in closed-die forgings during the heating to the austenitizing temperature before the quenching. Using this model, the heating and soaking times of the forgings in the furnace can be shortened, the optimum layout of the forgings in the furnace can be found and various types of problems solved.

In the model, all the heat-transfer modes were taken into consideration. The most effective method of the solution was sought, taking account of the accuracy of the results. Due to the complexity of the problem, the computation times of the simulation variants were on the order of hundreds of hours. The sizes of database files even exceeded 100 GB. For this reason, this model will continue to be developed in an effort to shorten the computation times and reduce the data storage requirements. Gradual improvement in the accuracy of the model is a matter of course.

The second application of the numerical simulation involved an analysis of a closed-die forging process for a selected forged part. This model was developed to obtain the temperature and strain data to be used as the input data in constructing a material/technological model. Such a model combines the findings from the numerical and physical simulations for assessing the feasibility of substituting the existing hardening process. The available alternative is the thermomechanical treatment (combining forming and the subsequent controlled cooling).

It was found that thermomechanical treatment can produce practically identical properties of a workpiece as conventional hardening. However, such results should be interpreted with caution and this finding should be supported by a larger body of statistical data. In future efforts, the FEM simulation of forming processes will be refined, e.g., using Johnson-Cook model for describing the plastic behaviour of a forged part instead of the curve plots employed so far.

Acknowledgement

This paper reports the results obtained under project TA02010390 "Innovation and Development of New Thermo-Mechanical and Heat Treatment Processes of Die Forgings by the Transfer of Findings Obtained from Material-Technological Modelling". The project runs in the framework of the ALFA programme and is funded from the specific resources of the state budget for research and development through the Technology Agency of the Czech Republic.

5 REFERENCES

[1] Marc® 2012, Volume A: Theory and User Information, User's manual

[2] I. Poláková, T. Kubina, Flow stress determination methods for numerical modelling, 22nd International Conference on Metallurgy and Materials, METAL 2013 , Brno, Czech Republic, 2013, 273– 278

[3] S. L. Semiatin, T. Altan, Measurement and Interpretation of Flow Stress Data for the Simulation of Metal-Forming Processes, Materials and Manufacturing Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio, USA, 2010, 1–57

[4] V. Pileček, F. Vančura, H. Jirková, B. Mašek, Material-Technological Modelling of the Die Forging of 42CrMoS4 Steel, Mater. Tehnol., 48 (**2014**) 6, 869–873