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MATERIAL-TECHNOLOGICAL MODELLING OF THE DIE FORGING OF 42CrMoS4 STEEL

MATERIALNO-TEHNOLOŠKO MODELIRANJE UTOPNEGA KOVANJA JEKLA 42CrMoS4

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Material-technological modelling is a tool for effective designing and optimizing real-world forming processes. It involves processing a small volume of a material in a thermomechanical simulator under the conditions corresponding to those of the real-world process: in this case it was die forging. By means of modelling, the effects of changed parameters on the existing processes and products can be explored. The present paper presents the development of a highly complex material-technological model of real die forging of the 42CrMoS4 steel. The data required for developing this model were obtained during the production in a forge. The characteristics that are not technically measurable, such as the strains at particular points of the forging, were determined with the aid of a FEM simulation. Upon comparing the outcomes of the process modelling and the real schedule, the final microstructures including their phases and morphological characteristics were found to match. The microstructure consisted of a ferrite-bainite mixture. The discrepancy between the HV10 hardness levels of the specimen and the actual forged part was less than 2 %.

Keywords: material-technological modelling, die forging, thermomechanical simulator, FEM simulation, 42CrMoS4

Materialno-tehnološko modeliranje je orodje za učinkovito načrtovanje in optimiranje realnih postopkov kovanja. Vključuje predelavo majhnega volumna materiala v termomehanskem simulatorju v razmerah, ki ustrezajo resničnemu postopku: v tem primeru je bilo to kovanje. Z modeliranjem lahko preučujemo vplive spremenjenih parametrov na sedanje procese in proizvode. Ta članek predstavlja razvoj kompleksnega materialno-tehnološkega modela za realno utopno kovanje jekla 42CrMoS4. Podatki, potrebni za razvoj tega modela, so bili izmerjeni med proizvodnjo v kovačnici. Lastnosti, ki jih tehnično ni mogoče izmeriti, kot so raztezki v določenih točkah, so bile določene s FEM-simulacijo. Primerjava ugotovitev iz modeliranja procesa in realnih razmer, končne mikrostrukture, vključno s fazami in njihovimi morfološkimi značilnostmi, je pokazala dobro ujemanje. Mikrostruktura je bila sestavljena iz mešanice ferita in bainita. Odmik med trdoto HV10 vzorcev in trdoto resničnih odkovkov je bil manjši od 2 %.

Ključne besede: materialno-tehnološko modeliranje, kovanje v utopu, termomehanska simulacija, FEM-simulacija, 42CrMoS4

1 INTRODUCTION

Following the trend of cost-cutting measures, the forging industry seeks new ways to enhance quality and productivity while reducing the production costs. Besides FEM simulations, another way to achieve this goal is by material-technological modelling (MTM).[1–3]

Material-technological modelling allows the proposed improvements of the existing die-forging technologies and the optimization of new processes to be verified using small volumes of materials processed in a thermomechanical simulator.

Material-technological model was already successfully prepared for other forming processes, such as wire rolling. After the verification of this model on a real product, this model was used to solve technological problems with the cooling of a coiled wire.[3] Another model was created for sheet rolling, where it helped to solve the problem of reduction sizes.[4] MTM can also be utilized for an application of low-alloyed TRIP steels.[5]

The modelling process corresponds to the conditions of the real forming process. Thanks to the results of the material-technological modelling one can obtain information about the microstructure and mechanical properties of the planned products. Changes to the process can be verified outside the production facility. Interference in the production process is thus eliminated.

The essential aspect of a valid material-technological model is the use of deformation-energy intensity and time dependences identical to the real-world process.[4–6] The validity of the model is tested by comparing its outcomes with the real part.

In this case, the part was made by die forging. Furthermore, the model is intended for validating the proposed changes to the present heat-treatment procedure which comprises hardening and controlled cooling.

2 EXPERIMENTAL WORK

The purpose of the experiment was to develop a material-technological model for a forged part from the 42CrMoS4 steel (**Table 1**). The forged part is intended as a drive shaft to a gearbox. The initial microstructure of the specimens consisted of ferrite and pearlite with a hardness of 310 HV10.

The real-world forged part was made in a crank press using four successive operations: upsetting, performing,

Table 1: Chemical composition of 42CrMoS4 steel (volume fraction, φ/%)
Tabela 1: Kemijska sestava jekla 42CrMoS4 (volumenski delež, φ/%)

Element	C	Mn	Si	P_{max}	S_{max}	Cu_{max}	Cr	Ni_{max}
φ/%	0.42	0.50 0.80	0.17 0.37	0.04	0.04	0.03	1.1	0.3

finish forging and trimming. The forming operations were followed by two-stage cooling: the cooling of separate forged parts on the conveyor and cooling down to the ambient temperature inside the heap of forged parts in a box.

Material-technological modelling was carried out with a thermomechanical simulator. The thermomechanical simulator provides accurate control and monitoring of the predefined parameters of thermomechanical processing. Its response times meet the requirements for high-strain rates. The forming-operation times are in the order of hundredths of seconds. The same performance is required from the temperature-control function. The specimens for the simulator have a diameter and a gauge length of 8 mm and 16 mm, respectively (**Figure 1**).

The agreement between the results of material-technological modelling and the features of the real-world forged part in particular locations was assessed by means of metallographic observation and HV10 hardness testing. Metallographic observation was carried out with light, scanning electron and laser confocal microscopes.

2.1 Determining the Key Process Parameters

For the material-technological model to be constructed, an analysis of the essential parameters of the forging process is necessary. These essential parameters were measured during the production. They included the temperatures and reductions during progressive forging and also the stages from heating in an inductor to still-air cooling. The temperature and time were measured on the die-forging line before and after each forming operation. For technical reasons, the temperatures were measured using a two-colour pyrometer. The instrument was positioned and fixed to measure a predefined region of the forged part. The progress of cooling on the conveyor was mapped with the pyrometer and a thermal imaging camera. Exact times of the operations were extracted from the press-ram records. The subsequent heat treatment of the forgings was tracked with the measurements taken on the continuous heat-treatment lines.

The strains and temperatures in various locations of the forged part, which were technically impossible to measure, were explored using a FEM simulation with the DEFORM software. The input data for the FEM simulations were acquired with the field measurements (times, temperatures, characteristics of forming machines) and by measuring mechanical and thermo-physical properties of the material at various temperatures (using compression tests at various strain rates).[7] By means of a macroscopic examination of the forged part and FEM simulation data, the points (**Figure 2**) for the temperature and strain (**Figure 3**) monitoring were identified. These data were employed for developing the thermomechanical-simulator program.

2.2 Development of the Material-Technological Model

The material-technological model for particular points on the forged-part cross-section was constructed from the results of the FEM simulations (**Figures 2** and **3**). The requirement of matching the strain-energy intensity of the real-world forged part was to be fulfilled by

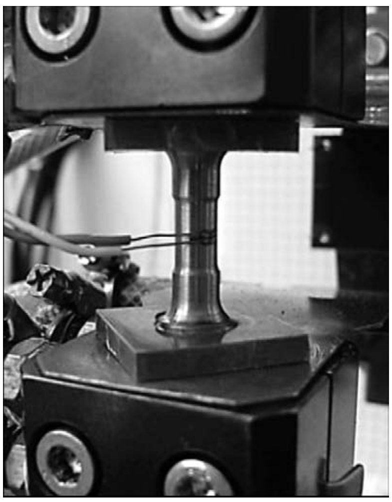

Figure 1: Specimen mounting in the thermomechanical simulator
Slika 1: Vpetje vzorca v termomehanski simulator

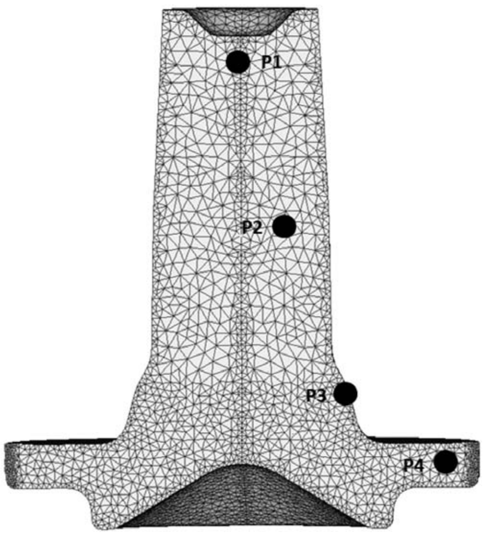

Figure 2: FEM-simulation: the section through the forged part
Slika 2: FEM-simulacija: prerez skozi odkovek

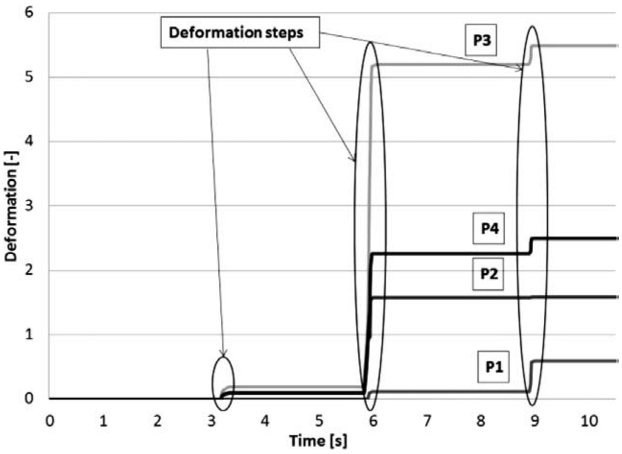

Figure 3: FEM simulation: strain-versus-time curves at various points on the forged-part cross-section

Slika 3: FEM-simulacija: krivulje odvisnosti raztezek – čas v različnih točkah prereza odkovka

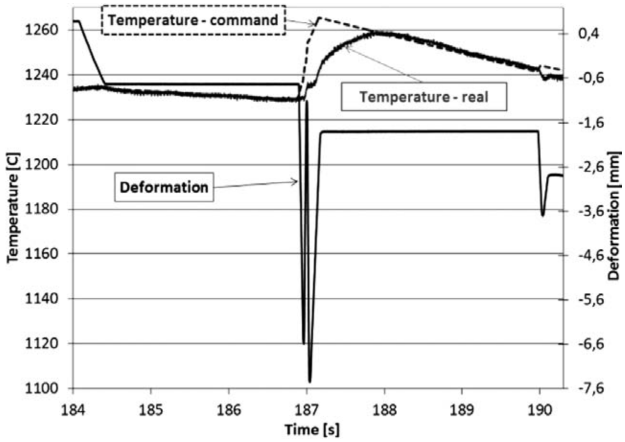

Figure 5: Detail of the strain region

Slika 5: Detajl področja pomika

converting the true logarithmic strain into the displacement of the thermomechanical-simulator deformation element. The specimen was only deformed in the axial direction.

The total true strain interval φ at various points on the cross-section was wide, ranging from 0.59 to 5.48. The point chosen for developing the first material-technological model was P4 (**Figure 2**). This point offers the best representation of the area of the forged part which is crucial from the viewpoint of loading on the final product. In this location, the total true strain was φ = 2.5. The largest increase in the strain occurred during the second forming operation, performing. This strain interval makes up almost 90 % of the total strain (**Figure 4**).

In order to accumulate the entire logarithmic strain within each forming step, the strain in the material-technological model for a particular point was divided into the tensile and compressive strain components (**Figure 5**). Otherwise, specimen instability would have occurred. At some points, the extension amounted to 90 % of the gauge length. It is not technically feasible to achieve this strain level by applying stable uniform deformation. This is why the strain in the test specimen should not exceed a certain limit corresponding to the lateral expansion of the specimen. With the heating method used, an excessive expansion of the gauge part would have prevented the required temperature field from being achieved and the temperature increase due to the strain energy introduced could not have been accounted for. The modelling plot shows that the actual temperature only slightly deviated at the stage of the temperature increase due to the deformation heat. The prescribed and actual strain plots match (**Figure 5**). Acknowledging the fact that the cooling rate is an important factor for a structure development, the cooling strategy after the deformation was also investigated. Two different cooling strategies were tested (**Figure 6**). In the first model, the cooling after the forming represented the cooling of an individual forging. In the second model, the cooling was separated into two phases. The first

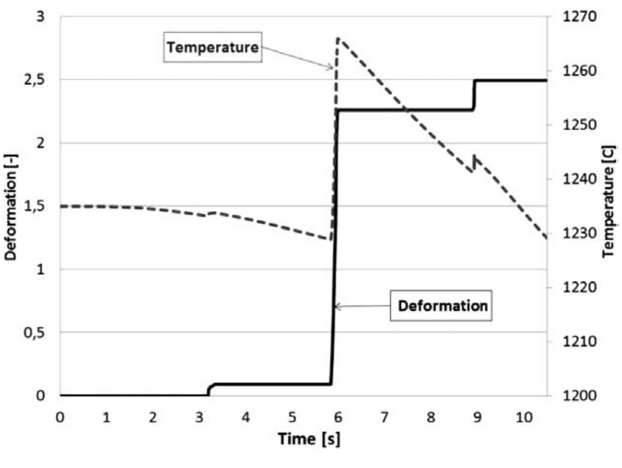

Figure 4: Detail of the deformed region according to FEM simulation: temperature and strain versus time plots

Slika 4: Detajl deformiranega področja pri FEM-simulaciji: krivulje temperatura in pomik v odvisnosti od časa

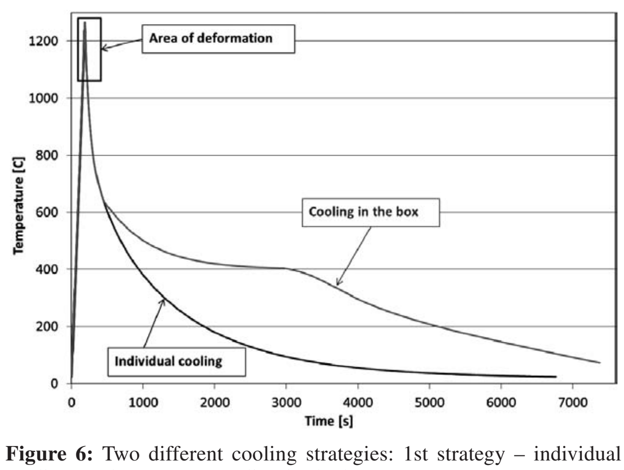

Figure 6: Two different cooling strategies: 1st strategy – individual cooling, 2nd strategy – cooling in the box

Slika 6: Dve različni strategiji ohlajanja: 1. strategija – individualno ohlajanje, 2. strategija – ohlajanje v škatli

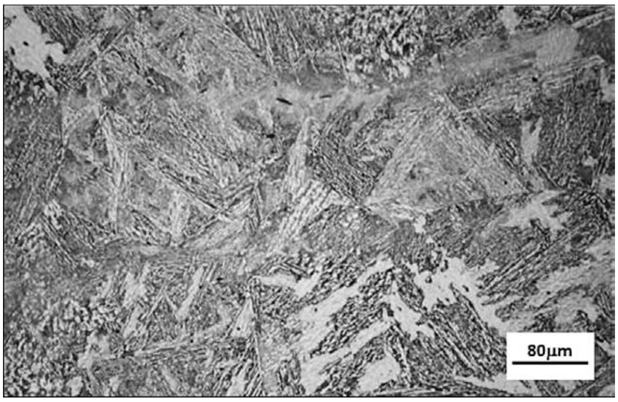

Figure 7: Laser-confocal micrograph of forged part: bainite-ferrite mixture, 315 HV10
Slika 7: Laserski konfokalni posnetek odkovka: mešanica ferita in bainita, 315 HV10

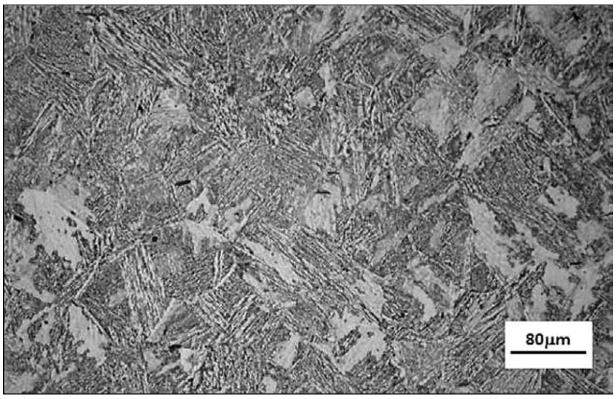

Figure 8: Laser-confocal micrograph of the material upon the simulation processing: mixture of bainite and ferrite, 310 HV10
Slika 8: Laserski konfokalni posnetek materiala po simulirani obdelavi: mešanica bainita in ferita, 310 HV10

phase, the cooling of an isolated forged part on the conveyor, immediately followed the forming operations. At the end of this phase, the temperature of the forged parts was in the range of 620–660 °C. The second phase comprised the cooling of multiple forged parts dropped off the cooling conveyor into a box. It was found by measuring the real-world process that while the box is being filled (over approximately 1 h), it retains an almost constant temperature (approximately 200 °C near its walls and approximately 400 °C in its centre). Once full, the box with the forged parts is transferred to a stock area where the parts cool down to the ambient temperature in the heap. The duration of this cooling phase depends on the weather conditions. The environment of the cooling box was mapped using coated Inconel thermocouples. The thermocouples were distributed among various points of the box to gain an insight into its temperature field. This cooling method was adopted upon a request for an optimization of the material-technological models.

3 RESULTS AND DISCUSSION

The prepared material-technological models were tested against the samples from material 42CrMoS4 using the thermomechanical simulator. The model with individual cooling of one forging was tested as well as the model with the cooling in the box filled with other forgings. The metallography and hardness values were subsequently compared with the real forging, which was documented in the position marked as P4.

After the MTM with the cooling of individual forgings, a very fine bainitic microstructure with a low fraction of free ferrite was obtained. This ferrite was in some cases found at the original austenite boundaries. The hardness reached 322 HV10. In the case of a slower cooling in the second model simulating the cooling of more pieces together in the box, a coarsening of bainite needles was observed. The amount of free ferrite in the resulting microstructure was also very low (**Figure 7**). Slower cooling resulted in a slightly lower hardness of 310 HV10.

The morphologies and distributions of individual phases after the processing according to the model with the cooling in the box corresponded to the microstructure obtained during real forging (**Figure 8**). The hardness of the real-world forging in the area corresponding to the modelled point was 315 HV10.

The results of the material-technological model were thus in a very good agreement with the real-world forged part in terms of both the microstructure and HV10 hardness. The difference between the hardness levels was a mere 5 HV10, which is approximately 2 %. The procedure was repeated for the other selected points located on the forged part.

4 CONCLUSION

The material-technological models for the selected points of a real forged part were developed. For the composition of these models, the data were obtained with the measurements taken during a real process and using a FEM simulation. The material-technological models were tested on the thermomechanical simulator. It was found that all the aspects of the processing have to be taken into account. The significance of the cooling rate in the last phase of the processing for the final morphologies of the phases was particularly noticed.

The resulting microstructures of all the tested models and also of the real forged part consisted of bainite and ferrite. At the monitored point of the forged part, the difference between the hardness of the model specimen and the real part was approximately 2 %. The relevance and adequate accuracy of the modelling procedure were thus confirmed. In future, this model will be employed for developing and optimizing the processes associated with forged parts and for developing manufacturing routes involving controlled cooling.

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