MATERIAL-TECHNOLOGICAL MODELLING OF CONTROLLED COOLING OF CLOSED DIE FORGINGS FROM FINISH FORGING TEMPERATURE

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Abstract

Mechanical properties of closed die forgings reflect their microstructure which is formed during the manufacturing process. There are a number of process factors at play which govern the final microstructural condition of the forged part. Besides the amount of working and the forging temperature, there is the post-forge cooling rate which has a decisive influence on the resulting microstructure. An important pre-requisite for dealing with these aspects is the definition of the input requirements and the boundary conditions. For instance, an input requirement may involve obtaining the desired microstructure within the entire forged part. Boundary conditions include the actual capabilities of the forge shop in terms of the control over the forged part's cooling. Hence, predicting the resulting properties of the forged part's material is a complex endeavour. In ordinary forge shops, there is no other way of finding these properties than by trial and error, which is rather demanding. It is time consuming and costly because a number of cooling routes must be tried in the plant. An alternative to this is material-technological modelling. It is a highly effective method of modelling the cooling of forgings without interfering with the production. By this means, the optimum manufacturing route can be found which, once implemented, delivers the desired microstructure of the forged part at minimized cost.

Keywords: Material-technological modelling, controlled cooling, 30MnVS6

1. INTRODUCTION

The economic perspective on production has been continuously gaining importance in recent years. The effort to monitor and cut production costs, while maintaining high quality of products, has been receiving increasing attention. The manufacture of forged parts comprises a number of operations and associated processes. The feedstock is forged and, typically, heat-treated upon forging. The decisive collection of requirements is the one defined by the customer. It may involve requirements on the final microstructure or on mechanical properties. To meet those, forgings often undergo heat treatment. An available alternative to such post-forge heat treatment is the controlled cooling of forgings from the finish-forging temperature. An appropriate cooling sequence can provide the desired microstructures and mechanical properties without the need for heat treatment. This can substantially improve the production efficiency. On the other hand, introducing a new sequence into production is time consuming and often costly. Testing and optimising the controlled cooling process directly in the plant does not guarantee a success. It is thus desirable to find the appropriate cooling conditions using another approach which allows the cooling parameters to be optimised without interfering in production operations. One of the available approaches is material-technological modelling (MTM). The underlying idea of MTM is to process a material sample using the same thermal and deformation inputs, sequences and temperature profiles as in the real-life process. The resulting microstructural evolution is thus identical to that in the actual process. The method involves constructing a detailed physical, material and process model which simulates the real-life manufacturing process [1, 2]. The required agreement between the problem specification and the process requirements is achieved by gradually updating the model.

2. EXPERIMENTAL PROGRAMME

The controlled cooling process described in this paper has been developed for the demonstration forging shown in **Fig. 1**. This forging is used in the chassis of a lorry. Its present manufacturing route comprises four progressive forming operations: upsetting, preforming, finish forming and trimming, followed by heat treatment which involves quenching and tempering. With respect to the planned change in the manufacturing route, the existing 42CrMoS4 material was substituted in this experiment with the 30MnVS6 microalloyed steel, so that ferritic-pearlitic microstructure could be achieved.

Fig. 1 Forged part used for the demonstration

2.1. Development of Material-Technological Model

The material-technological model describes the manufacturing route for the present forged part. In order to develop it, extensive measurements have been undertaken on-site at VIVA forge. They included time profiles for heating and cooling processes, the durations of operations and times between operations. The measurement data was used for constructing FEM models of temperature profiles of processes employed in the manufacture of the forging. Those processes include forging, post-forge cooling and heat treatment [3]. Using FEM calculations, the forging process was simulated (**Figs. 2 and 3**). The simulation data provided detailed information on temperature, strain rate and strain distributions throughout the forged part. The simulation calculations were then used for developing the material-technological model of the entire manufacturing process. The accuracy and information value of the model were verified by comparison with the actual forging [4, 5]. Metallographic characterisation and mechanical testing proved a substantial agreement between the model and the corresponding parts of the real-life forged part.

Process of material-technological modelling is carried out on a thermomechanical simulator - Flex Test SE MTS 810 Material Test System . The simulator offers precise control and short response times in performing the thermomechanical treatment even at high strain rates and in demanding thermal schedules. The specimens - round rods with threaded ends have a diameter of 8 mm, with gauge length 16 mm, are heated by combination of induction and resistive heating.

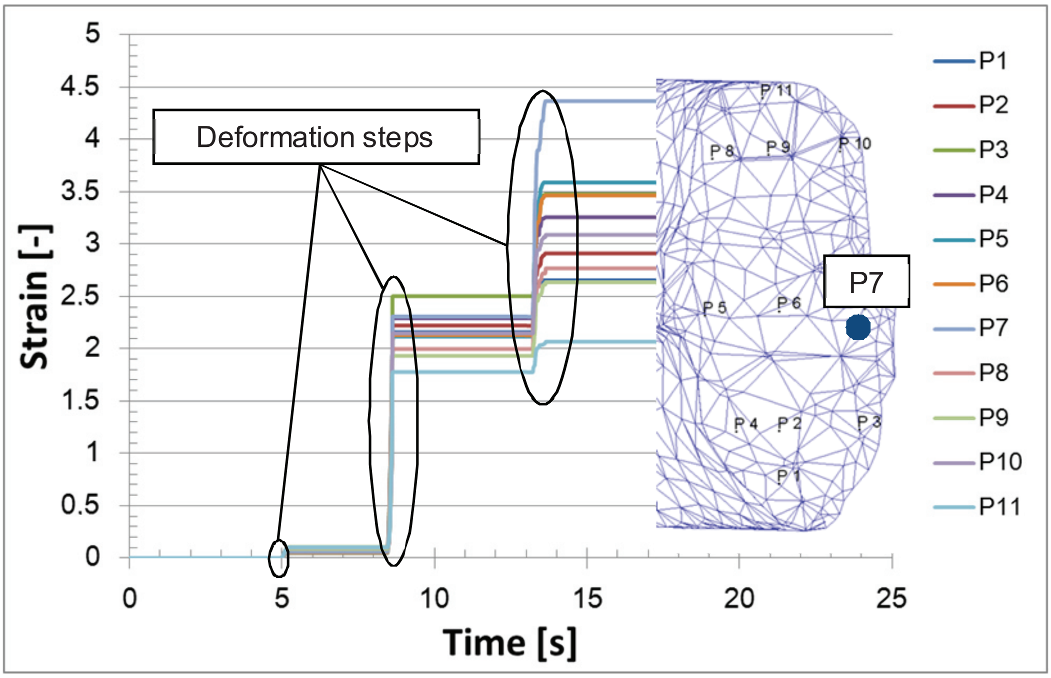


Fig. 2 Strain profiles for selected locations on a cross-section through the forged part

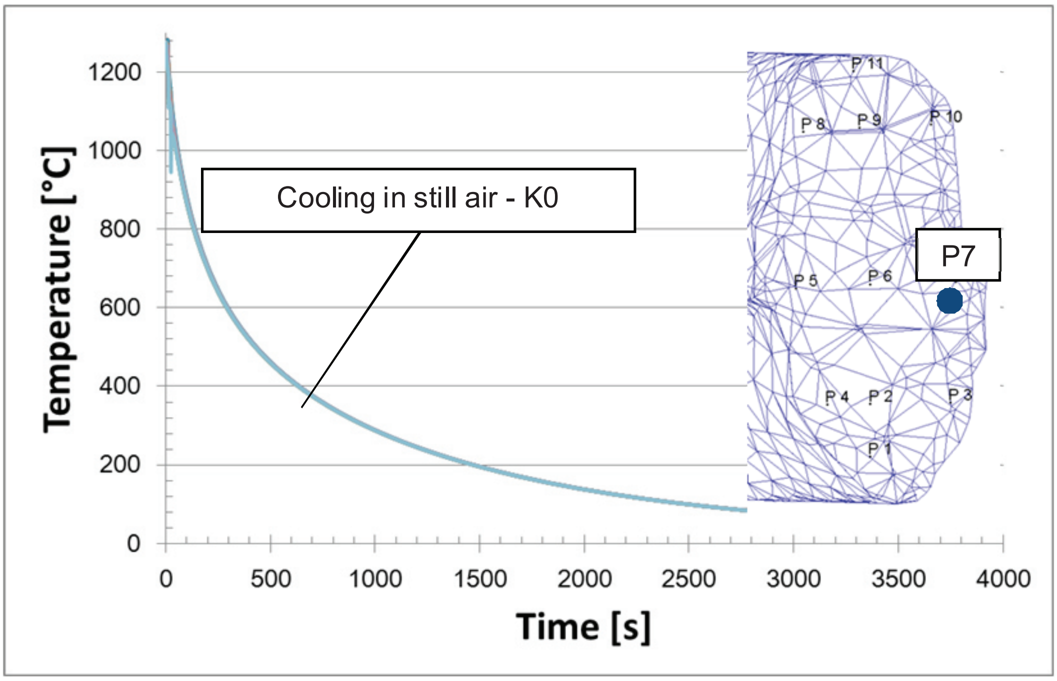
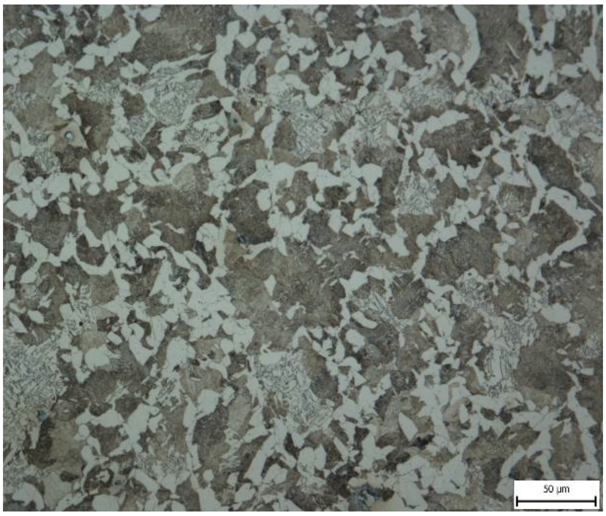


Fig. 3 Temperature profiles at selected points on the forged part cross-section during cooling in still air - K0

For the purpose of material-technological modelling of controlled cooling from the finish-forging temperature, a critical cross-section was subsequently identified and the relevant model has been constructed, the temperature profile of which followed the cooling of the selected P7 point in still air (**Fig. 3**). This point was chosen with respect to the highest total logarithmic strain φ=4.4 achieved on the cross-section in question. The model thus comprised and described both forging and post-forge cooling operations.



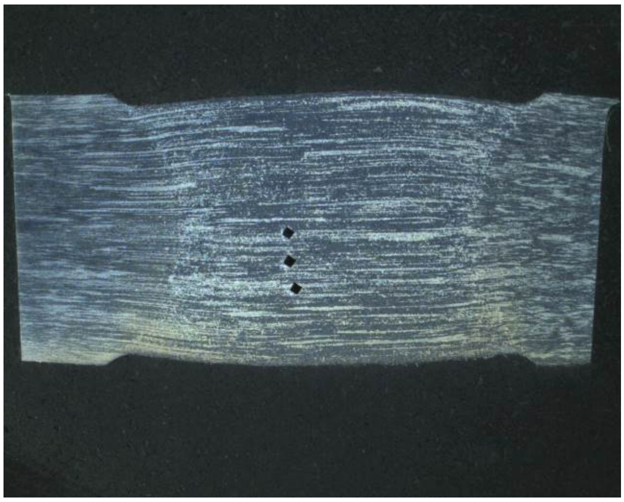


Fig. 4 Left: microstructure of the modelling specimen replicating the P7 point after cooling still in air - K0 cooling curve. Right: macrostructure on the cross-section through the modelling specimen

In this modelling specimen, ferritic-pearlitic microstructure with some bainite has been found (**Fig. 4**). The distribution and fraction of bainite become visible after macroetching. Bainite appears as bright bands. The specimen with this microstructure showed a hardness of 269 HV10. Based on this value, temperature profiles for the cooling process of the forged part were proposed and a processing window was defined for achieving the desired microstructure by controlled cooling (**Fig. 5**). The desired microstructure consists of no other phases but ferrite and pearlite. The cooling rate required for producing this microstructure was sought in the critical temperature range of 950/300 °C. Under the experimental programme, a large number of cooling curves have been constructed. For the sake of clarity, only some of them are mentioned here.

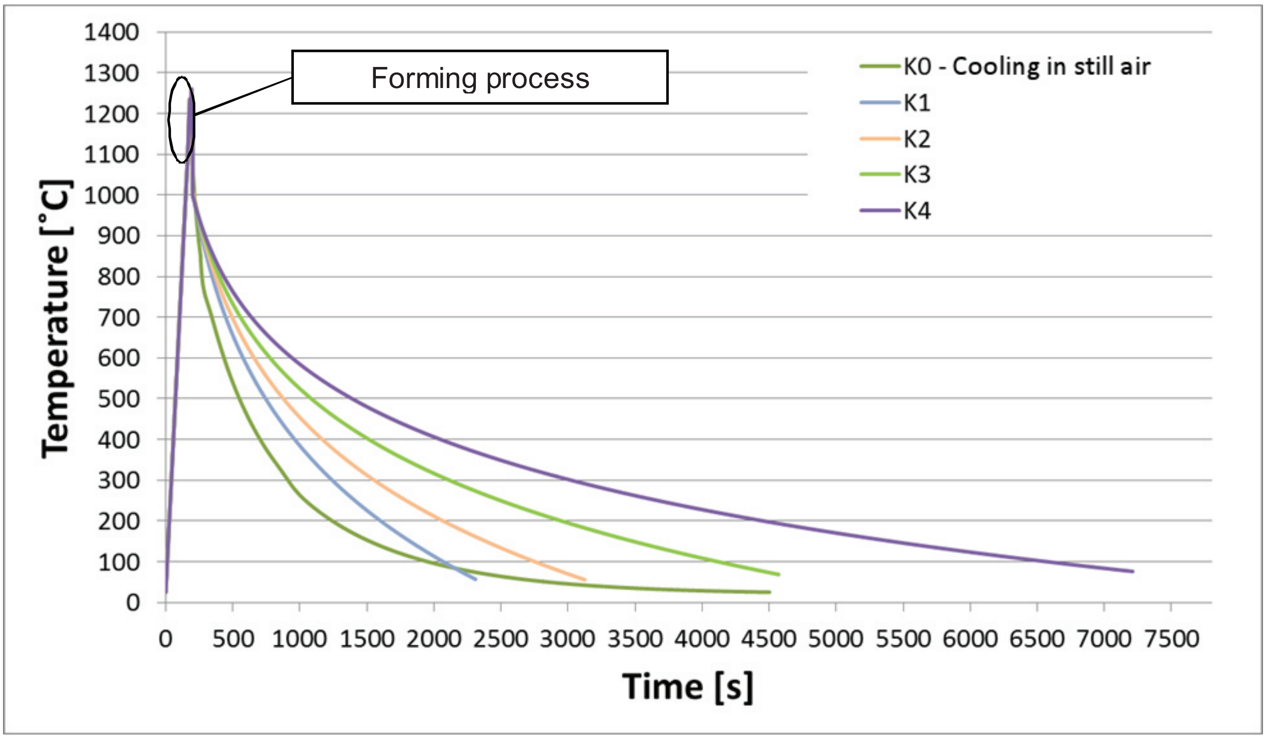


Fig. 5 Controlled cooling curves at the P7 point of the forging

3. RESULTS AND DISCUSSION

The cooling of the modelling specimen according to K1 curve led to a ferritic-pearlitic microstructure with a certain fraction of bainite which, however, was substantially smaller than upon cooling in still air according to K0 curve (**Fig. 6**). The fraction and distribution of bainite become apparent after macroetching. The hardness of this modelling specimen was 264 HV10. The slower cooling according to K2 curve led to a microstructure of ferrite, pearlite and a small fraction of bainite (**Fig. 7**). In this case the hardness value was 259 HV10.

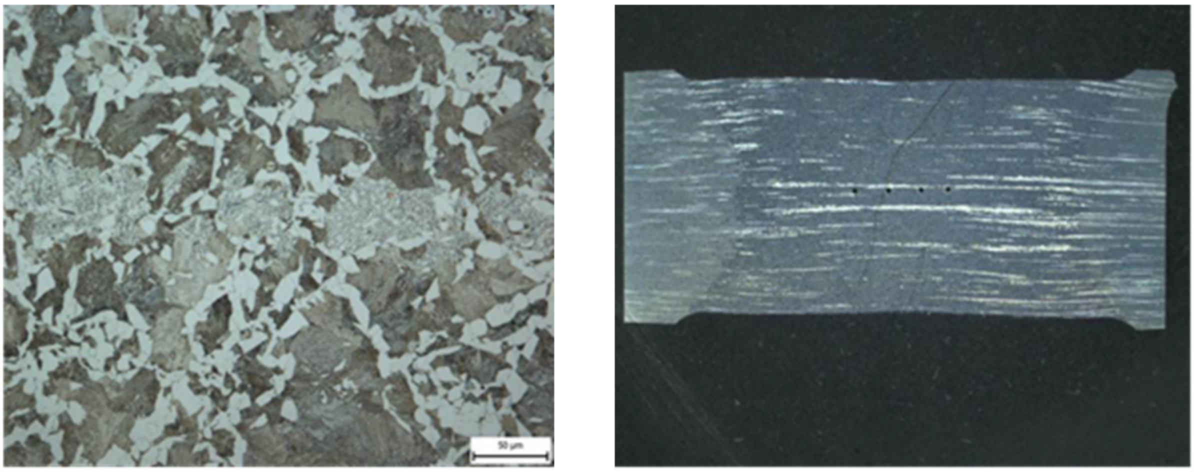


Fig. 6 Left: microstructure of the modelling specimen replicating the P7 point - controlled cooling according to K1 cooling curve. Right: macrostructure on the cross-section through the modelling specimen

The microstructure of the modelling specimen which had cooled according to K3 curve consisted of ferrite and pearlite (**Fig. 8**). Its hardness was 246 HV10. The controlled cooling from the finish-forging temperature according to K4 curve produced a bainite-free mixture of ferrite and pearlite (**Fig. 9**). The hardness of the modelling specimen was 235 HV10.

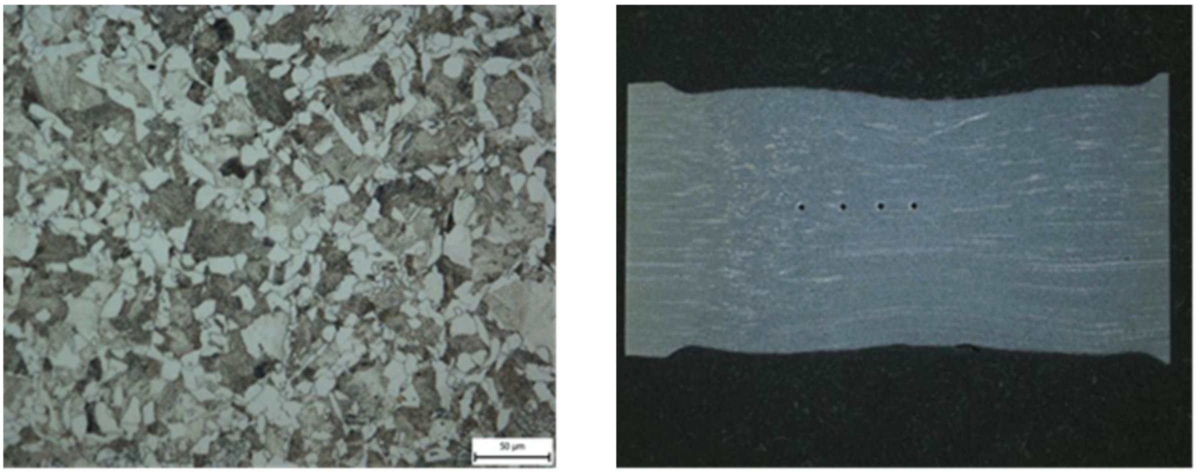


Fig. 7 Left: microstructure of the modelling specimen replicating the P7 point - controlled cooling according to K2 cooling curve. Right: macrostructure on the cross-section through the modelling specimen

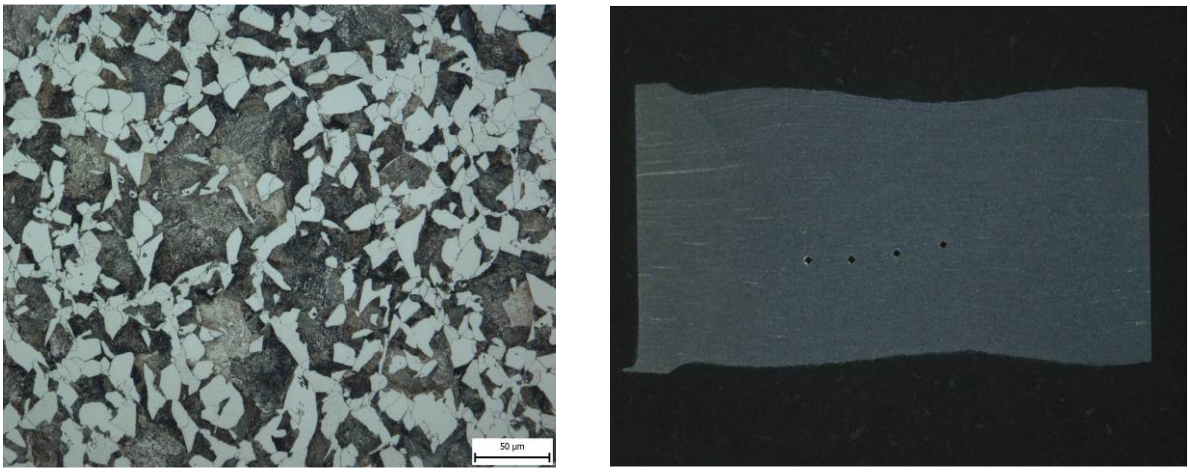


Fig. 8 Left: microstructure of the modelling specimen replicating the P7 point - controlled cooling according to K3 cooling curve. Right: macrostructure on the cross-section through the modelling specimen

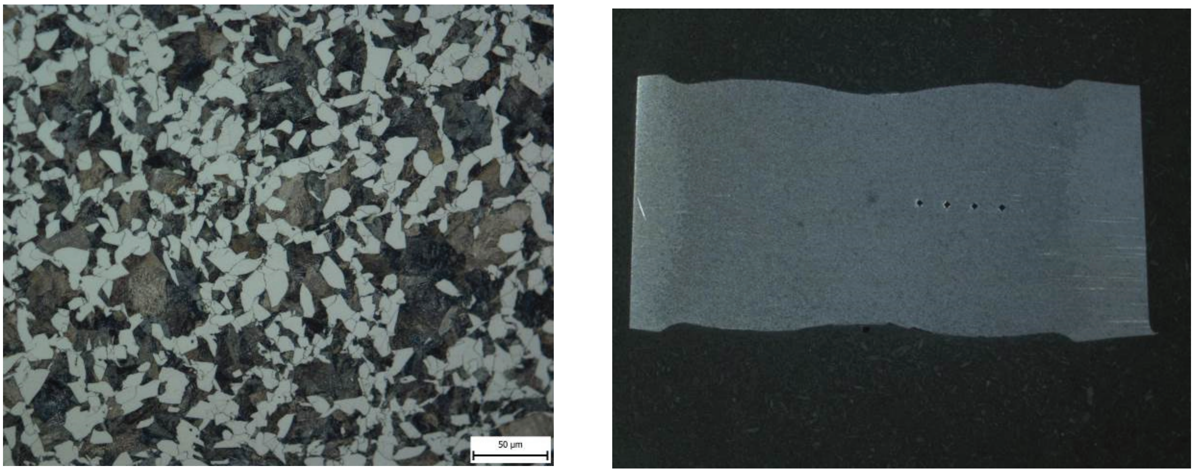


Fig. 9 Left: microstructure of the modelling specimen replicating the P7 point - controlled cooling according to K4 cooling curve. Right: macrostructure on the cross-section through the modelling specimen

4. CONCLUSION

Savings in the production of closed-die forgings were a motive for developing and implementing a manufacturing route which eliminates heat treatment and allows the final microstructure and properties to be achieved by direct post-forge cooling. The approach used for this development was material-technological modelling. Thanks to this approach, the potential for substituting the current material with microalloyed steel could be explored. In addition, information has been obtained on the process parameters and the microstructural evolution. Using the data acquired on-site, i.e. in the forge shop, and FEM simulations, models of the manufacturing route, including forming and heat treatment, have been developed and verified. Based on these models, controlled cooling from the finish-forging temperature has been proposed and optimised. Associated with this step was the substitution of the original 42CrMoS4 steel with the 30MnVS6 microalloyed steel. Thanks to these changes, energy cost savings and shorter production lead times can be attained. The present controlled cooling models have been designed with the purpose of documenting the dependence of microstructural evolution on the cooling rate in the critical 950/300 °C range. Appropriate cooling parameters for achieving ferritic-pearlitic microstructure throughout the forged part have been found by the research. The experiments showed that cooling within the 950/300 °C critical range must take longer than 1600 seconds. If the cooling becomes faster, bainite begins to form, which is undesirable for the forging type in question.

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REFERENCES

[1] MAŠEK B., JIRKOVÁ H., MALINA J., SKÁLOVÁ L., MEYER L. W. Physical Modelling of Microstructure Development During Technological Processes with Intensive Incremental Deformation. Key Engineering Materials, 2007, Vol. 345-346, No. 1-2, pp. 934-946, ISSN 1013-9826.

[2] MAŠEK B., JIRKOVÁ H., KUČEROVÁ L., RONEŠOVÁ A., MALINA J. Material-Technological Modelling of Real Thin Sheet Rolling Process. METAL 2011. 20th Anniversary International Conference on Metallurgy and Materials, 2011, pp. 216-220. Edit. TANGER Ltd., ASM Int, Mat Informat Soc; CSNMT; VSB-TU. ISBN 978-80-87294-24-6.

[3] FEDORKO M., MALEČEK L. Construction of Numerical Model of Forging Process of Four-Pole Rotor Shaft. Hutnické listy, 2012, Vol. LXV, No. 4, ISSN 0018-8069.

[4] PILEČEK V., VANČURA F., JIRKOVÁ H., MAŠEK B. Material-Technological Modelling of Die Forging of

[5] 42CrMoS4 Steel. Materiali in technologije, 2014, Vol. 48, Issue 6, pp. 869-873, ISSN 1580-2949.

[6] VOREL I., PILEČEK V., VANČURA F., JIRKOVÁ H., MAŠEK B. Material-Technological Modelling of C45 Steel Die Forgings. Procedia Engineering. (DAAAM 2014), 2015, Vol. 100, Issue C, pp. 714-721, ISSN 1876-6102.