Using of material-technological modelling for designing production of closed die forgings

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Abstract. Production of forgings is a complex and demanding process which consists of a number of forging operations and, in many cases, includes post-forge heat treatment. An optimized manufacturing line is a prerequisite for obtaining prime-quality products which in turn are essential to profitable operation of a forging company. Problems may, however, arise from modifications to the manufacturing route due to changing customer needs. As a result, the production may have to be suspended temporarily to enable changeover and optimization. Using material-technological modelling, the required modifications can be tested and optimized under laboratory conditions outside the plant without disrupting the production. Thanks to material-technological modelling, the process parameters can be varied rapidly in response to changes in market requirements. Outcomes of the modelling runs include optimum parameters for the forging part’s manufacturing route, values of mechanical properties, and results of microstructure analysis. This article describes the use of material-technological modelling for exploring the impact of the amount of deformation and the rate of cooling of a particular forged part from the finish-forging temperature on its microstructure and related mechanical properties.

1 Introduction
A large number of parameters play their roles in forging processes. The key ones include temperature and strain magnitude and rate. Their values together with cooling conditions impart the resulting properties to forged parts. It is often impossible to map their effects in actual operation, mainly due to financial constraints associated with production.

One available solution is the use of material-technological modelling. This method involves simulating the real-world forging process in a laboratory in order to study the effects of process parameters without interrupting or slowing down production in the forge shop [1]. As a result, countless trials can be run which – if carried out in the factory – would entail a major financial burden. The product of material-technological modelling is a specimen with a processing history identical to the actual manufacturing route for the forged part [2, 3]. Unlike FEM simulations, this approach enables microstructure characterization and mechanical testing. Its design requires concrete data gathered in real-world production. This data, i.e. temperatures, intervals between operations, and cooling rates, as well findings from the FEM simulation of the forming process, including deformation values, are used for developing material-technological modelling specifications [4, 5,6,7].
Figure. 1 General view of the forged part, a cross-section with the points selected for modelling, and their total true strain levels.

2 Experimental

This material-technological modelling study was conducted to correlate true strain levels and the rate of cooling of a particular forged part from the finish-forging temperature with resulting microstructure and mechanical properties. This forging is used for making part of the drive train of a lorry “Figure 1”. Its final microstructure was specified as a mixture of ferrite and pearlite. Material-technological models were constructed for several points on the forging’s cross section. For these points, FEM simulations using the DEFORM software reported the following true strain levels: φ = 0.8; 1.8; 3.6; 5.5. Cooling curves starting at the finish-forging temperature were plotted for these points “Figure 2”. The curves, i.e. the associated cooling rates, were designed to enable a particular limit cooling rate to be identified: the one at which no bainite forms in the material within the critical cooling interval of 950/300 °C.

Figure. 2: a) Cooling rates from the finish-forging temperature in the material-technological models of the chosen points, b) Profiles of true strain introduced during forging operation.

Modelling was carried out in a thermomechanical simulator provided with an electrical induction-resistance heating system which offers heating rates of up to 100 °C/sec. The specimens obtained by material-technological modelling were sectioned to prepare metallographic sections and provide stock
for static tensile testing and notch toughness testing. The experimental material was 30MnVS6 steel “Figure 3”.

**Figure 3.** CCT diagram for the 30MnVS6 steel as computed and constructed using the JMAtPro program.

3 Results and discussion

3.1 Mechanical properties

The values of mechanical properties confirmed the expectation that the strength of material increases with the amount of deformation “Figure 4” and the tensile test was applied using small flat specimens machined from the deformed parts with dimensions of 5 mm reduced section and a cross section 2 mm × 1.2 mm. The strength level was also affected by the rate of cooling from the finish-forging temperature “Figure 5”. The highest strength was obtained for K1 cooling curve. By contrast, the lowest strength – at an identical amount of strain – was obtained upon cooling according to K5 curve. This effect of cooling rate is probably down to the resulting fractions of phases (ferrite, pearlite, and bainite), and to the presumed precipitation of vanadium carbides within proeutectoid ferrite and within the ferrite in pearlite.

**Figure 4.** Tensile strengths of specimens representing material-technological models with various total strain levels and cooling rates.

**Figure 5.** Elongation A5mm of specimens representing material-technological models with various total strain levels and cooling rates.
The highest elongations, 30–33 %, were attained upon cooling according to K5 curve “Figure 5”. By contrast, the lowest elongations, A5mm = 28–24 %, were obtained upon cooling according to K1 curve. This relationship between the cooling rate and the A5mm elongation is attributed to ferrite fraction, which increases with decreasing cooling rate. On the other hand, A5mm elongation decreased with increasing amount of strain, as expected “Figure 5”. This is in agreement with the general principles of deformation behaviour of metals.

![Figure 6. Notch toughness KCV of specimens representing material-technological models with various total strain levels – K5 cooling curve.](image)

![Figure 7. Hardness number HV10 of specimens representing material-technological models with various total strain levels and cooling rates.](image)

Impact toughness tests using charpy impact samples were carried out on specimens which had cooled according to K5 curve “Figure 6” due to the final microstructure of its samples. The charpy samples were also machined from the deformed parts with dimensions of 2 mm thickness, 4 mm × 27.5 mm as a cross section, the geometry of the notch is 1 mm deep with angle of 60° and maximum radius 0.1 mm. This curve was chosen because of the requirement for the material-technological modelling specimens to contain fully ferritic-pearlitic microstructure. Notch toughness values (KCV) showed a flat peak at approx 40 J/cm². The lowest notch toughness levels were found in specimens with true strains of φ = 5.5. Interesting information about the impact of deformation on fracture behavior was thus obtained. The expectation that at higher strains, and therefore higher work-hardening levels, the notch toughness will decrease considerably, was not confirmed entirely. Macrohardness was measured in the specimens “Figure 7”. It increased linearly with true strain, with highest levels at φ = 5.5, and the lowest values at φ = 0.8. This correlation with deformation is probably related to the essential principles of work hardening and precipitation hardening. The lowest hardness was found in specimens which had cooled according to K5 curve. The highest hardness was obtained with the K1 curve. This can be explained by the various ferrite, pearlite, and bainite fractions. The lowest amounts of pearlite (and correspondingly higher amounts of ferrite) were found in specimens which had cooled according to K5 curve, as opposed to specimens cooling according to K1 curve.

3.2 Metallographic examination
The microstructure of the specimen was revealed with 3 % nital and examined under optical microscope. All specimens which had cooled according to K1 curve consisted of ferrite, pearlite, and a small amount of bainite “Figure 8”. Bainite was also found in specimens cooling according to K2 curve. K3–K5 curves led to ferritic-pearlitic microstructures “Figure 9”. With increasing true strain, the microstructure became notably finer, as the size of ferrite, pearlite and bainite grains and particles decreased “Figure 10, 11”.

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Figure 8. Micrograph of specimen cooling according to K1 curve, total strain $\varphi = 0.8$.

Figure 9. Micrograph of specimen cooling according to K5 curve, total strain $\varphi = 0.8$.

Figure 10. Micrograph of specimen cooling according to K5 curve, total strain $\varphi = 1.8$.

Figure 11. Micrograph of specimen cooling according to K5 curve, total strain $\varphi = 5.5$.

4 Conclusion
Using material-technological modelling, correlation between true strain levels, the rate of cooling of a particular forged part from the finish-forging temperature and the resulting microstructure and mechanical properties was examined. Several points were identified on the forging’s cross section. For these points, FEM simulations using the DEFORM software reported the following true strains: $\varphi = 0.8; 1.8; 3.6; 5.5$. Material-technological models were constructed for these points to describe the forging process in thermophysical terms. One boundary condition for this study required the final specimens to contain exclusively ferritic-pearlitic microstructure. Important conclusions have been drawn from the experiment and verified. Tensile strength increased with the amount of strain in individual specimens, each of which represented selected points on the cross-section through a forged part. This effect can be strengthened by accelerated cooling through the critical interval of 950/300 °C. Elongation decreases with increasing amount of strain and cooling rate. Notch toughness shows a flat peat at 40 J/cm$^2$. Hardness decreases with cooling rate. The hardness of the forged part can be optimized for machinability by appropriate cooling. The prescribed ferritic-pearlitic microstructure can be obtained by cooling through the 950/300 °C interval in more than 1600 seconds.

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