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HOT FORMING AND HEAT TREATMENT SIMULATION IN A STEEL MILL

CHRISTIAN REDL[1], BAOHUI TIAN[1], VOLKER WIESER[1], CHRISTOF SOMMITSCH[2], THOMAS WLANIS[2]

[1] Böhler Edelstahl GmbH, 8605 Kapfenberg, Austria
[2] Christian-Doppler-Laboratory for Materials Modelling and Simulation, 8700 Leoben, Austria

Abstract

Numerical simulation is nowadays becoming a standard tool in industrial processes. This paper provides an insight about the usage of finite element calculations in the development and production process in the steel mill of Böhler Edelstahl GmbH, Kapfenberg, Austria.

Simulation methods are used all along the value chain at the mill starting with melting and casting of the steel. Nevertheless this paper focuses on the simulation of hot forming and heat treatment as well as on the simulations done as a service for our customers.

Considering as example a hot work tool steel of type 1.2343 the production chain from forging over the pre heat treatment at the mill to the application as a tool for aluminium extrusion is surveyed. The forming of the casted and remelted steel block is done on a radial forging machine (swaging machine) of the type GFM SX55. The simulation takes into account five passes and delivers strains and temperatures within the work piece. Afterwards the pre heat treatment cycle of the part consisting of heating, quenching in polymer solution and subsequent air cooling is modelled.

Simulation services are provided to the customers to optimize the material selection for their specific applications. The aforementioned tool steel is used as liner or die material in the extrusion industry. By a combination of a visco-plastic material model and a damage model it is possible to predict the lifetime of the tools in use.

In order to obtain the residual stresses and phase distribution after nitrogen quenching a heat treatment simulation of the die is performed. Afterwards a simulation of the extrusion process is carried out to get the distribution of effective stress and temperature in the die. The calculated life time as well as the predicted location of the maximum damage agrees well with observations from real extrusion processes.

Key words: simulation, radial forging, heat treatment, life time prediction, hot work steel

1. INTRODUCTION

Böhler Edelstahl GmbH (BEG), part of the Böhler-Uddeholm group, is one of the largest tool steel manufactures in the world with an annual capacity of 150,000 tons. Numerical simulation based on the finite element method is an integral part of the product and process development. Fig. 1 shows the flow of material through the steel mill of BEG in Kapfenberg (Austria). The circles indicate process steps where simulation tools are currently applied for optimisation and quality assurance.

The paper focuses on the numerical simulation of forming and heat treatment processes. Other fields of application are vacuum arc remelting (VAR, Reiter et al (2005)) and protective gas electro slag remelting (P-ESR, Schützenhöfer et al (2006)).

The following example illustrates the application of simulation tools along the production chain of a hot work steel block eventually used as die material in the aluminium extrusion industry. The chemical composition is given in table 1.

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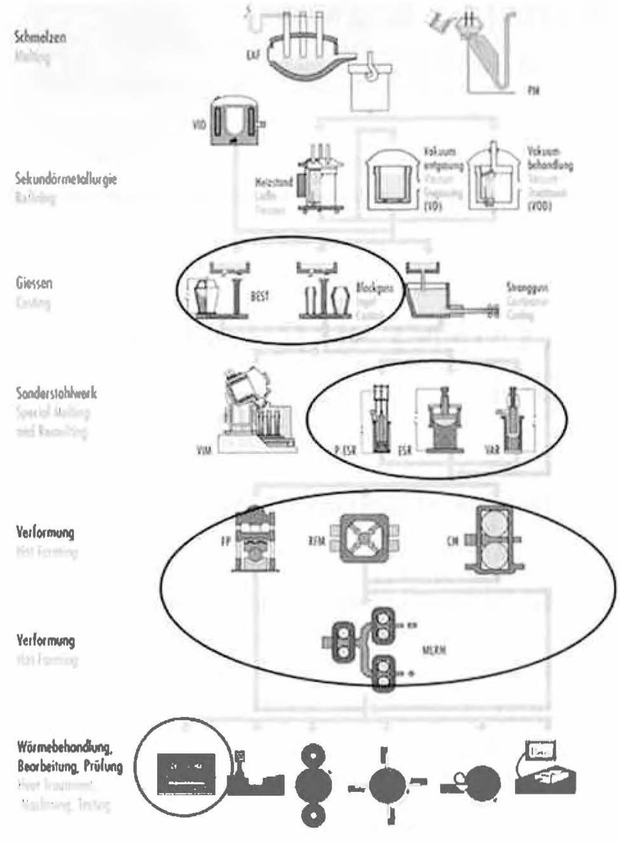

Fig. 1. Flow of material.

The forging as well as the heat treatment simulations have been carried out using DEFORM™. For the simulation of the extrusion process and the life time prediction Abaqus™ is used.

2. FORGING SIMULATION

An octagonal block with a width across flats of 450 mm is forged in five passes to a round bar with a final diameter of 288 mm. The work piece is preheated in a rotary hearth furnace to 1100°C and is transferred within 90 seconds to the radial forging (swaging) machine (type GFM SX55). The rate of strokes is 200 per minutes and the rotation between subsequent strokes is 13.5°. The feed rate for the present case is 5 m/min.

The cogging module of DEFORM 3D™ enables the simulation of complex forging processes as a one step procedure. Figure 2 depicts the computational model for the radial forging. The model consists of 6000 finite elements leading to a simulation time of about one week for the entire process. Boundary conditions such as friction coefficient, heat transfer to the environment etc. are considered. Experiences with forging simulations are reported in Harrer (2005a, 2005b).

Table 1. Chemical composition of Böhler W400VMR

Grade	Mat. #	DIN	C[%]	Si[%]	Mn[%]	Cr[%]	Mo[%]	V[%]
W400VMR	~1.2343	~X38CrMoV5 1	0.36	0.2	0.25	5.0	1.3	0.45

The requirements on steel used for extrusion tools are manifold: Thermal stability, high working hardness, high thermal conductivity etc. These properties are not only dependant on the chemical composition but also on the following production steps: The steel Böhler W400VMR[1] is remelted under vacuum (VAR) to reach the highest degree on cleanliness and isotropy. A final special heat treatment guarantees an excellent annealed condition.

The production route of the steel Böhler W400VMR consists of melting and casting and the already mentioned remelting in a vacuum arc furnace. The block is forged and undergoes a special heat treatment before it is sold to the customer. After the manufacturing of the tool the final heat treatment follows. Simulation examples of the forging, of both heat treatment steps and of the extrusion process are presented to illustrate the application of numerical tools at BEG.

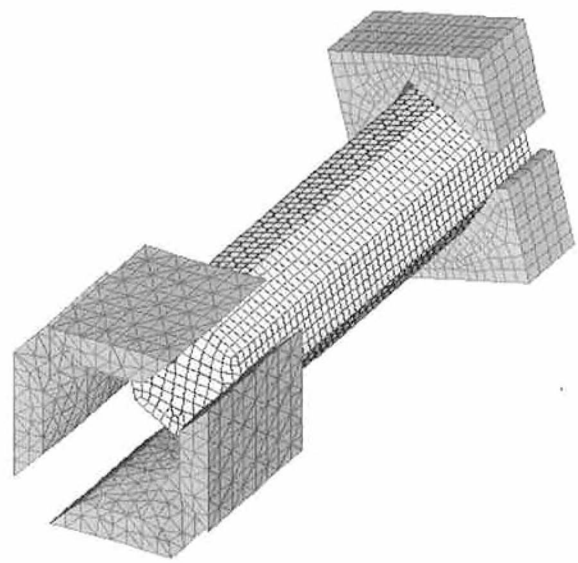

Fig. 2. FEM model of the radial forging process.

Figure 3 illustrates the effective strains after each pass. It can be clearly seen, that during the first passes the forming takes place only in the shell. Due to the yet lower diameter and an increased draught the centre of the bar is deformed in the final pass.

[1] The term VMR stands for *V*acuum *M*elted or *R*emelted.

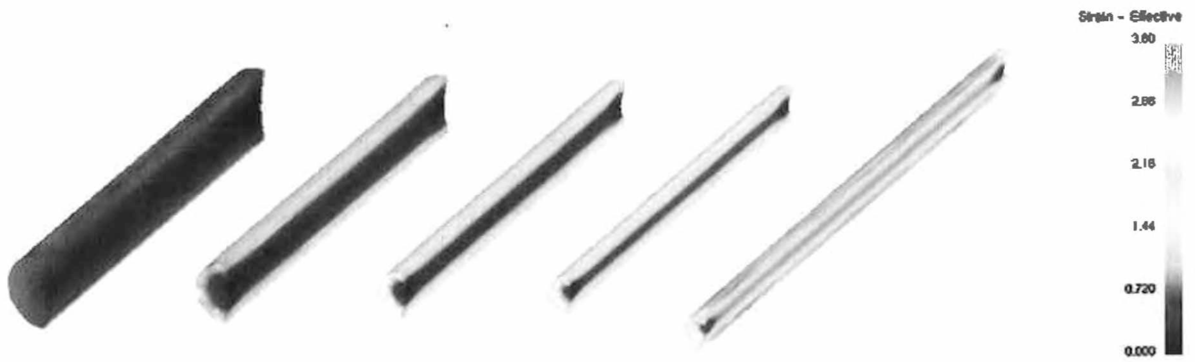

Fig. 3. Effective strain after each pass.

The temperature distribution within the bar is shown in figure 4. Due to the deformation heat the temperature in the centre is increased to 1130°C, whereas at the exposed ends of the work piece it is only about 800°C.

Fig. 4. Temperature distribution after the 5th pass.

3. SIMULATION OF HEAT TREATMENT AT THE STEEL MILL

After the forging the work piece is transferred to the heat treatment shop for annealing and austenitisation at 990°C. The usual quenching medium for this steel grade was oil, which had to be replaced by another hardening agent due to ecological and safety considerations. In contrast to oil the cooling effect of water or polymer solutions is much rougher, which may cause breaking of big steel blocks. It is therefore important to estimate the magnitude of residual stresses during quenching.

The heat transfer coefficient for the polymer solution was determined by experiments for different temperatures and polymer concentrations. In the heat treatment model the transformations from austenite to martensite (temperature controlled diffusionless transformation) and bainite (diffusion transformation based on TTT curves) and the corresponding transformations during tempering are included. Transformation plasticity, transformation latent heat and volume change are considered in the following simulations. A description of the used models and a sensitivity analysis pointing out the relative importance of the above mentioned transformation related effects is presented in Redl et al (2006a).

After austenitisation the block is quenched for 18 minutes and afterwards it cools down to ambient temperature in air. Figure 5 shows the maximum effective (von Mises equivalent) stresses within the block for polymer and water quenching. The first stress peak for polymer quenching after about 7 minutes is due to the start of the phase transformation at the surface. The second steep increase of the stress can be associated with taking out the block from the quenching media. The global maximum stress for polymer quenching is well below the yield stress for this steel grade. Compared to water quenching the maximum stresses are almost halved. Based on this result it was decided to use polymer solution as quenching medium.

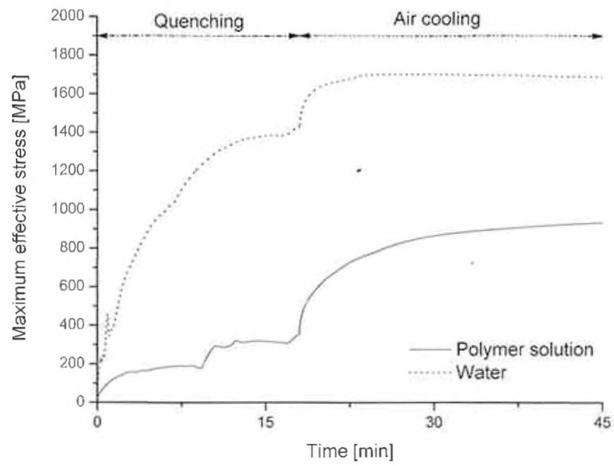

Fig. 5. Global maximum of the effective stresses.

4. SIMULATION OF FINAL HEAT TREATMENT

Simulations of e.g. extrusion processes are done to optimize the material selection for the customer's applications. As already mentioned before the tool steel Böhler W400VMR is used as liner or die material in the aluminium extrusion industry. A verification of the heat treatment models for different hot work tool steels on CrMoV-basis is given in Schützenhöfer et al. (2005).

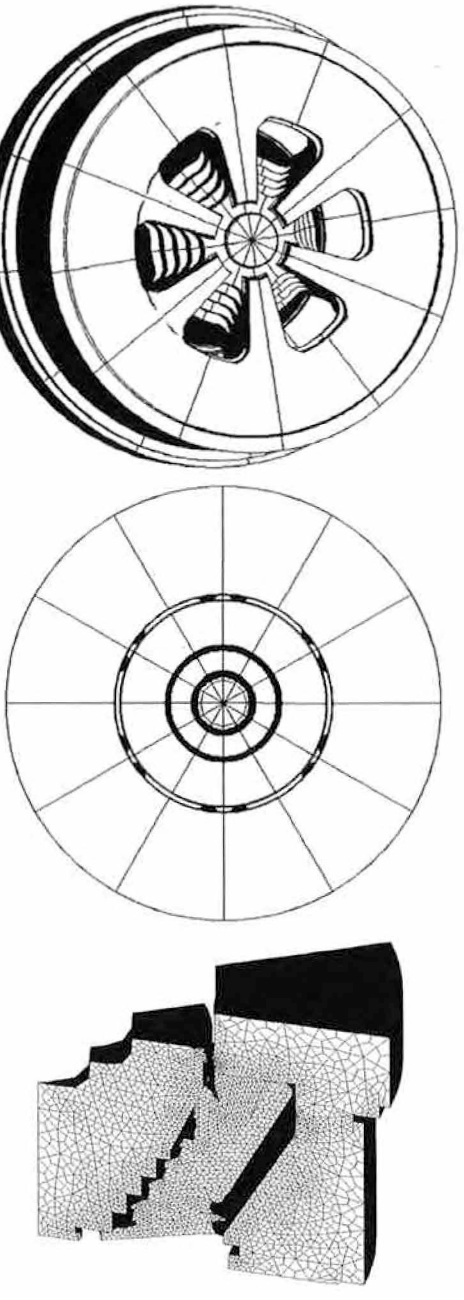

Fig. 6. Model of a die for tube extrusion.

In the present example a die for extruding aluminium tubes is considered. The tool is depicted in figure 6. The diameter of the tool is 670 mm and the maximum thickness is about 260 mm. Due to the symmetry only a 30° part of the die is modelled.

First a heat treatment simulation is conducted to obtain the microstructure and residual stress state after hardening and tempering. In the present case the heat treatment is performed in a vacuum furnace using nitrogen at 3 bar as quenching medium followed by three times tempering. The material properties used in the subsequent process simulation depends on the obtained microstructure and the residual stress distribution is used as initial state in the extrusion simulation.

After hardening about 96% volume fraction of martensite and 4% volume fraction of retained austenite can be determined from the calculation (figure 7 left). The maximum effective stresses (von Mises equivalent stress) after hardening appear at exposed positions on the die as it can be seen in figure 7 (right). During tempering the retained austenite dissociates and the tetragonal martensite is transformed into tempered martensite. The residual stresses within the die are substantially lowered and equilibrate across the tool.

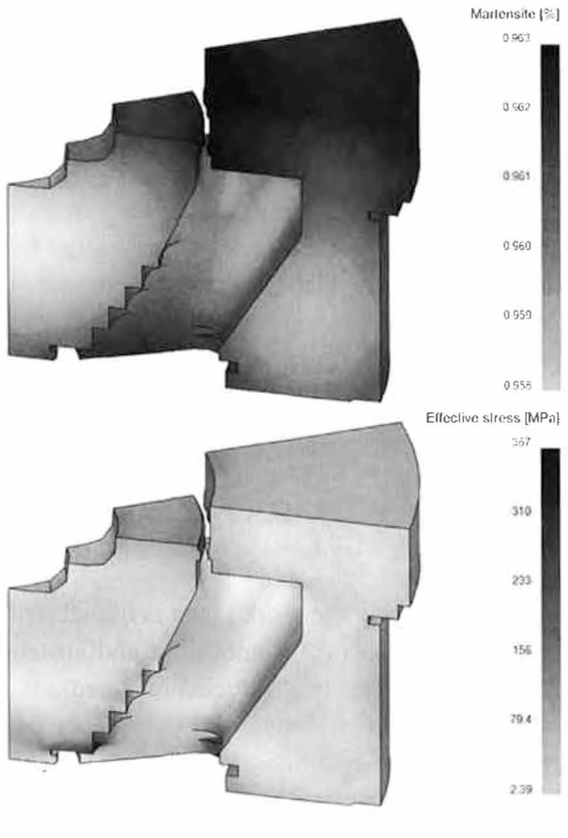

Fig. 7. Microstructure (top) and residual stresses after hardening.

5. DAMAGE MODELLING AND LIFE TIME PREDICTION

To simplify matters the simulation of the extrusion process is split into two parts. First the thermal and mechanical loads acting on the die are obtained by an extrusion simulation assuming rigid tools. These loads are afterwards applied as time dependent boundary conditions for a simulation where an elastic die is considered.

The material behaviour is described by a visco-plastic model according to Chaboche (1993). In order to predict the life time of highly stressed tools the inelastic stress-strain response has to be assessed. The influence of the thermo-mechanical history can be described by internal variables and their evolution equations, which are expressed as flow and hardening rules. It should be mentioned that all material properties must be determined within a 470 to 590°C temperature range. Details about the model can be found in Redl et al (2006b).

Cyclically loaded structures suffer a fatigue failure. Fatigue lifetime means in a macroscopic model the initiation of a macro-crack (typically a fraction of millimeter). Time incremental lifetime rules (e. g. Yeh and Krempl (1993)) evaluate the total damage in each time increment and, thus, can be applied to complex multiaxial loading paths, for which the definition of a single loading parameter describing the entire cycle could be difficult. Furthermore, a time incremental lifetime rule can easily be implemented in a material subroutine for finite element analysis of structures just as an evolution equation for an additional internal variable, the lifetime consumption.

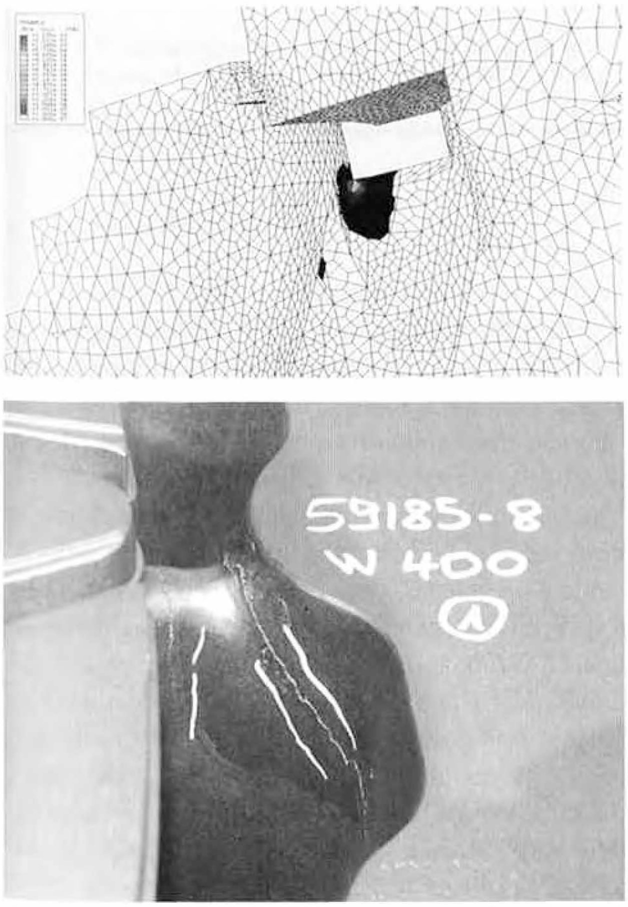

Fig. 8. Damaged extrusion die: Calculated (top) and reality.

Using the aforementioned procedure the thermo-mechanical loadings on the tool have been determined for the extrusion of an aluminium billet. Within each extrusion cycle that consists of a press time of 300 s and a loading time of 300 s, both the heat of the billet as well as the applied radial stresses have been defined by the above described boundary condition at the contact surface billet-die.

The maximum temperature (about 540°C) appears near the contact area billet-die, and the maximum von Mises equivalent stress of 730 MPa is also located in this area. The largest accumulated damage occurs in regions with disadvantageous overlapping of creep and fatigue (i. e. maximum overlapping temperature and equivalent stress loading). In figure 8 the region with maximum damage is highlighted and the location corresponds well to the observed cracks in reality (figure 8 (bottom)). The predicted life time is about 3,300 press cycles. Considering the idealised process conditions assumed in the simulation this agrees well with reported life times, which are between 1,500 and 3,000 press cycles.

6. CONCLUSION

The paper gives an overview on the simulation activities in the steel mill of Böhler Edelstahl GmbH. The focus is on forging and heat treatment processes. The simulation results (microstructure and residual stress state) of the final heat treatment of the tool are the basis for the process simulation and eventually the life time prediction.

The simulation of radial forging makes high demands on computer power and results in long calculation times. Additionally an in-depth knowledge of the characteristic of the forging aggregate is indispensable.

The results of the heat treatment simulation are well proven at least for CrMoV-type hot work steels in view of microstructure. To obtain realistic residual stresses after heat treatment the thermo-physical data of each involved phase and their transformation characteristics must be known accurately. At present time the phase transformation models rely in principle on dilatometric experiments. Of course transformation models on a sound physical basis would be even of great interest.

The extrusion simulation is done to obtain the boundary conditions for the subsequent damage modelling. The life time prediction, currently in a developing stage, delivers promising results. Nevertheless it must be noticed that the experimental procedure to obtain the necessary set of material properties is very complex.

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MODELOWANIE PROCESÓW ODKSZTAŁCANIA NA GORĄCO I OBRÓBKI CIEPLNEJ PROWADZONYCH NA WALCOWNI

Streszczenie

W pracy zaprezentowano przegląd zastosowań metody elementów skończonych w przedsiębiorstwie Böhler Edelstahl GmbH, Kapfenberg w Austrii. Wspomaganie komputerowe wykorzystywane jest na wszystkich etapach produkcji począwszy od topienia i odlewania poprzez plastyczną przeróbkę i obróbkę termomechaniczną skończywszy na przystosowaniu produktu do potrzeb odbiorcy. Jako przykład wykorzystania MES do symulacji pełnego cyklu produkcyjnego wybrano wytworzenie narzędzi stalowych wykorzystywanych do procesu wyciskania aluminium. Duży nacisk położono na ocenę zużycia oraz określenia czasu przydatności do użytkowania gotowego wyboru. Uzyskane wyniki wykazują duża zgodność z rzeczywistym zachowaniem się matrycy podczas procesu wyciskania.

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