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MATERIALS MODELLING IN INDUSTRIAL BULK METAL FORMING PROCESSES AND PROCESS CHAINS

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Abstract

Bulk metal forming processes range from processes with a single deformation step such as certain closed-die forging operations to processes with many subsequent stages such as hot rolling, ring rolling or open die forging. Modelling of these manufacturing processes requires both precise process models as well as adequate material models. Microstructure evolution by recrystallization is decisive in all of these processes since the microstructure determines the flow stress and hence the forming forces but it also influences the product properties. In this context, the propagation of variations in the processing conditions and in the material behavior are of special importance and methods for the quantification of uncertainties and their effect on model predictions are required. Such questions can be approached using models of different complexity on various scales as shown in the following examples: In closed die forging of a gear wheel from 25MoCr4 alloy the complex geometry requires a Finite Element process model which in this case is combined with a JMAK type material model. In plate rolling a simplified process model can be applied successfully. Based on the slab theory, which is enhanced for spatial resolution of shear strain using a meta model derived by FEM, this model can simulate even longer roll pass schedules within seconds and offers the possibility to combine it with numerical optimization techniques. Recrystallization of a high-manganese steel in interpass times between hot rolling passes is an example where models with spatial resolution (CP-FEM and phase field) are combined on the micro-scale to predict the recrystallization kinetics based on physically meaningful variables such as grain boundary mobility. In ring rolling the process model must include the closed-loop control system of the rolling machine to achieve a realistic prediction of the process kinematics. Feedback control loops for up to eight kinematic degrees of freedom (velocities and positions of all radial, axial and guiding rolls) have been defined using virtual sensors integrated in the simulation. Offline coupling with microstructure simulation is used to predict the final grain size and determine under which conditions static recrystallization occurs during the rolling sequence.

Key words: microstructure evolution, bulk metal forming, recrystallization, uncertainty quantification

1. INTRODUCTION

The importance of numerical simulation has increased considerably in recent years, especially in hot working. A primary driver for the widespread use of numerical simulation are economic and environmental requirements such as increasing cost pressure, shorter development cycles, and the increasing need to reduce material consumption and preserve resources. On the macroscopic scale, finite element models prevail in hot working. They provide both spatial and temporal resolution of field variables such as temperature, velocity, strain, strain rate and stress, but they also yield global properties like forming forces. Hot working operations such as open-die forging, flat or ring rolling impose multiple deformation passes on the workpiece, which are separated by interpass times or deliberate heating cycles. The microstructure undergoes tremendous changes in such processes. To analyse, design or improve hot working processes using finite element

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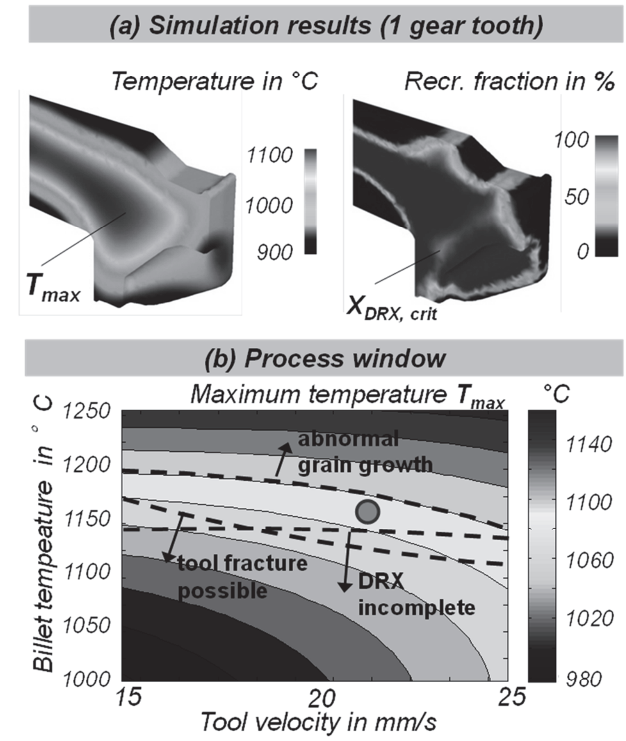
simulations, it is vital to have a constitutive model at hand that describes the material's response to external loads as accurately as possible. In hot working, the microstructure evolves primarily by recrystallization and grain growth. The flow stress is the main link between the macroscopic process simulation and the evolution of microstructure due to recrystallization and grain growth on the micro- and submicron scale. Particularly in multi-stage or incremental hot forming operations, a successful process simulation requires that the complex microstructural evolution can be accurately predicted as a function of the deformation history. It is hence essential for multi-stage metal forming processes such as plate or ring rolling to couple the development of the microstructure to the evolution of flow stress. To meet the demand set out by hot working operations, microstructure-based flow stress models were developed and integrated into FEM programs in the past. These models are typically so-called JMAK models without spatial resolution. In recent years, models with spatial resolution of the microstructure have been developed to allow for a deeper insight into the local phenomena governing microstructure evolution during and after hot working. To allow for predictive simulations of processes which crucially depend on feed-back control in reality, coupling of process models with the control algorithms of the real process is necessary, which further increases the complexity of metal forming simulations.

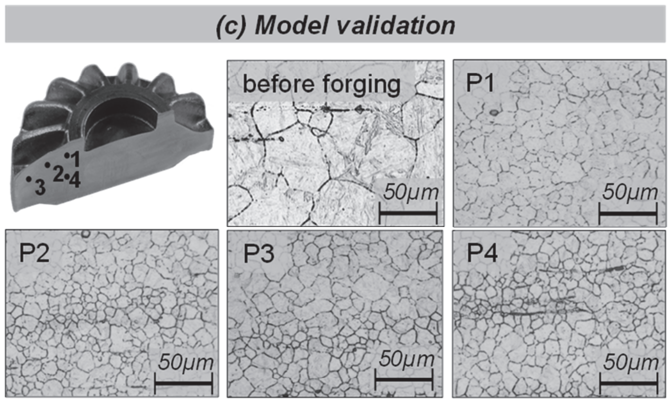
This paper details applications of JMAK models and spatially resolved microstructure evolution models to selected hot working processes such as gear wheel forging, plate and ring rolling, as well recent work on modeling static recrystallization using a sequentially coupled crystal-plasticity and phase-field models. In addition, the coupling of closed-loop feed-back control with an FEM model for ring rolling is presented.

2. MODELING GRAIN SIZE EVOLUTION IN GEAR WHEEL FORGING INCLUDING UNCERTAINTY

Hot-forged gear wheels are widely used, e.g., in drive systems of heavy-duty equipment. They have to provide mechanical properties such as high surface hardness, static strength, root bearing capacity, toughness and fatigue resistance. Although the final mechanical properties are determined largely by the heat treatment, high strength and fatigue resistance can be accomplished only if a homogeneous, fine-grained microstructure is obtained in the gear wheel after hot forging. When only the hot forging process is considered, the process chain essentially consists of heating, forming and cooling. The hot forging process is affected by uncertainties in the material behaviour, the process boundary conditions and the processing conditions. For robust design of the gear wheel forging process, it is necessary to quantify all uncertainties contained in the model input and trace them to the model predictions such as the final grain size. Uncertainty propagation for the gear wheel forging was discussed in detail in a previous publication by Henke et al. (2013). It was shown that a certain resampling method can be used to reveal the probability distribution of the final average grain size after hot forging and cooling, thus providing information about the uncertainty of the model predictions instead of providing only a single deterministic value. The basic model used by Henke et al. (2013) was a standard Finite Element model for the forging process which was coupled to a JMAK microstructure evolution model.

In this paper, the results published previously are enriched with more recent results. The main mechanisms creating an unwanted microstructure are abnormal grain growth and incomplete dynamic recrystallization. The occurrence of these phenomena is largely controlled by the initial temperature and the tool velocity. The billet temperature changes by heat transfer and dissipation, which are taken into account in the model. At lower forging temperatures, a finer grain size can be obtained but the risk of tool fracture increases. Varying the initial billet temperature and the tool velocity thus allows for identifying the process window shown in figure 1b which is bounded by abnormal grain growth at higher temperatures and incomplete DRX and possible tool fracture towards lower temperatures. The process simulation in figure 1a yields the maximum temperature after dissipation, which is used to create the map in figure 1b, as well as information on the completion of DRX and the occurrence of abnormal grain growth. An elastic simulation of the tool load reveals the possibility of tool fracture. The approach makes it possible to determine safe process conditions (grey dot in figure 1b), which yield the desired part with a homogeneous microstructure. The model validation with experimental results shown in figure 1c reveals a good conformance of model predictions and experimental results.





	Measured grain size *in µm*	Simulated grain size *in µm*
P1	12.3	13.6
P2	12.8	11.2
P3	12.6	10.2
P4	15.2	12.9
P5	14.2	13.4

Fig. 1. *Simulation of gear wheel forging with FEM+JMAK (a), determination of a process window for gear wheel forging (b), comparison of simulation and experimental results (c).*

3. FAST MATERIALS AND PROCESS MODELLING FOR PLATE ROLLING

Plate rolling is a flexible bulk metal forming operation where a slab with up to 900mm in thickness is rolled down to the desired thickness in ~5 to 40 passes. Some of the passes are used to control the final width of the product. In principle, plate rolling can be modelled by a full-scale FEM model, which is very time consuming for pass schedules with many passes. Alternatively, the "slab method" (see e.g. Sims (1954)) for the fast prediction of rolling forces used in this paper can be used. It is based on the assumption that the velocity in rolling direction only depends on the current position in the roll gap but is constant in thickness direction. Sims also proposed to introduce a geometric correction term that compensates the model inaccuracies introduced by the simplified assumptions. For hot rolling it is crucial to integrate a thermal description of the rolling process and additionally consider the microstructural changes. Still neglected even in recent fast rolling models is the fact that friction and the roll gap geometry produce shear strains that can influence the flow stress and the microstructure evolution. Kawalla and Schmidtchen (2013) addressed this issue using a so called "Layer Model". Another approach recently proposed by Seuren et al. (2014) is to extract the shear strain profiles from FEM simulations and integrate them into a fast rolling model based on the slab method. A comparison of the equivalent strain profiles calculated by the FEM and the fast rolling model for a thick and a thin slab is shown in figure 2a. The resulting through-thickness profiles differ for thick and thin slabs due to roll gap geometry, but the agreement between FEM and the fast rolling model is excellent. The additional information about the deformation gained from the shear strain model can be combined with a local temperature distribution of the roll stock that is obtained via an FDM model. Hence, it is possible to predict the microstructure in through thickness direction over all roll passes. In figure 2b it is clearly visible that the different forming conditions $\left(\varepsilon_v, \dot{\varepsilon}_v, \vartheta\right)$ over the thickness of the slab have a notable influence on the roll stock's microstructure. For an extended description of the fast rolling model capabilities for microstructure prediction as well as the modelling see Lohmar et al. (2014b).

All models for bulk metal forming depend on material parameters to match the materials behaviour during and after forming. To determine these parameters conventionally lab-scale material characterization tests are used to obtain flow curves and recrystallization kinetics. Those results are then used to fit the parameters for the material currently under

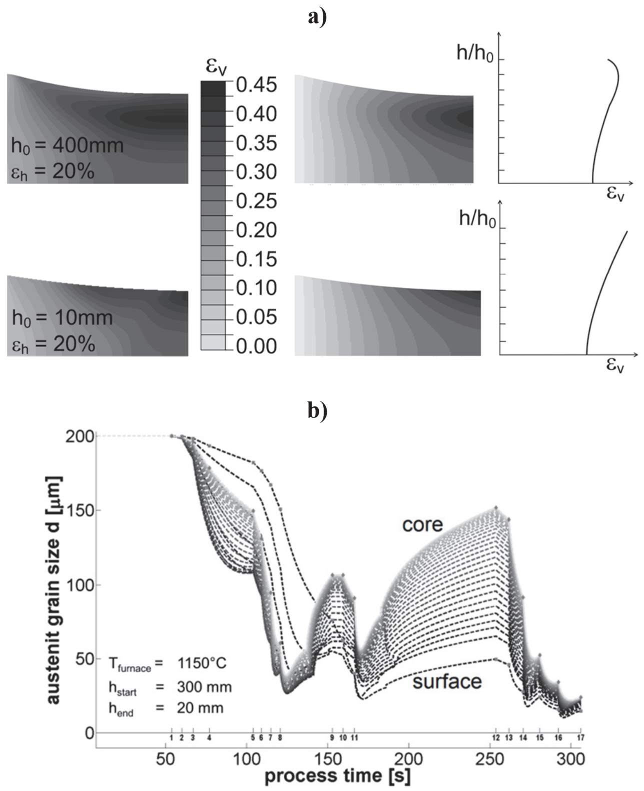


Fig. 2. Comparison of the equivalent strain in the roll gap obtained from FE-simulation and the fast rolling model for thick and thin plate (a), grain size evolution over the roll schedule and in through-thickness direction of the roll stock (b).

consideration directly. Szeliga et al. (2002) suggested replacing the direct evaluation by an inverse analysis of the basic laboratory tests using FE technique to increase accuracy. Still using the conventional approach for a multitude of different materials e.g. for over 200 steel grades typically found in plate rolling is infeasible due to the high experimental and financial effort. Here inverse techniques can also help as industrial field data, i.e. roll forces, torques and temperatures which are typically collected and archived in a rolling mill, can serve as reference data to calibrate the material model parameters and hence material testing becomes obsolete.

In this concept the deviation between the roll force prediction by the fast rolling model using some arbitrary parameters and the actual measurement can serve as indicator to evaluate the precision of the material model parameters. Reducing the roll force deviation of several slabs at a time by optimizing the parameters thus directly corresponds to improving the material model. Technically speaking the initial material model parameters are fed into an optimization loop as depicted in figure 3a. This loop is interrupted once the deviation of calculation and

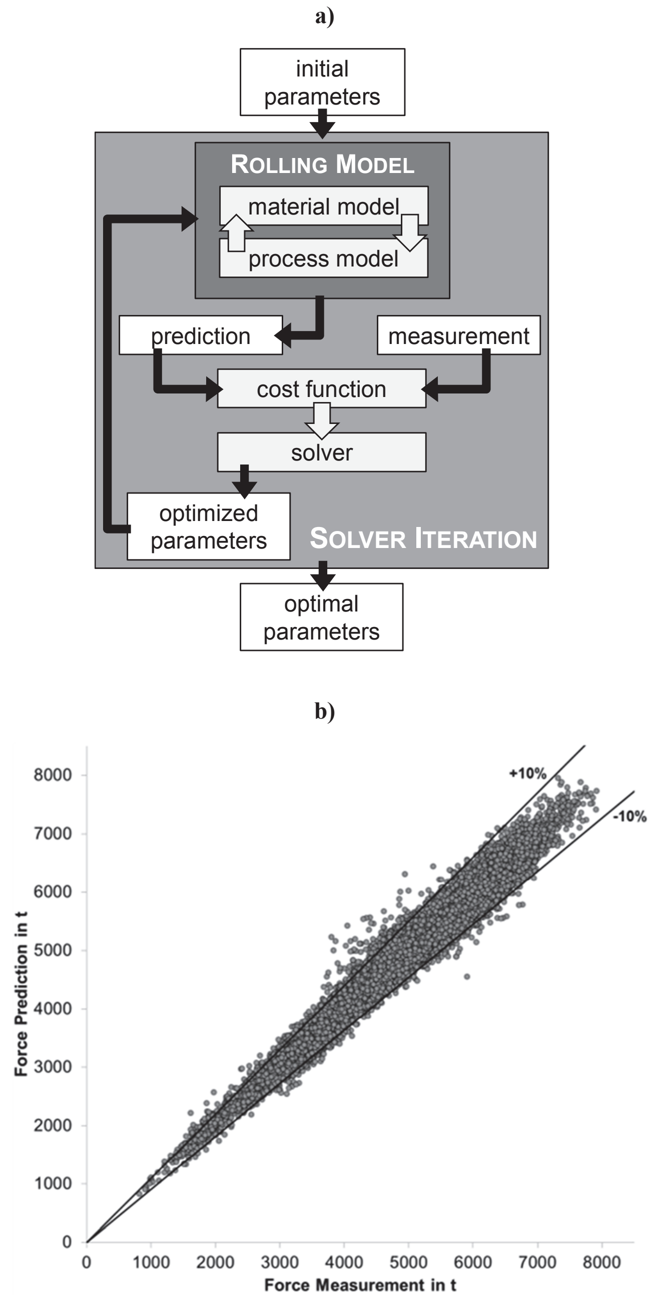


Fig. 3. Flow chart of the inverse approach for material parameter determination (a), measured and predicted forces from a single optimization run (b).

measurement drops below a cut off value and the optimal parameters are returned. Using this concept covered in detail in publications by Lohmar et al. (2014a, 2014c) only the computational costs rise if the number of considered materials is increased. By combining the inverse approach and the fast rolling model, the results shown in figure 3b can be obtained. Here, a cluster of different micro-alloyed low carbon steel grades with in total 88.000 roll passes was used as input. The resulting optimal parameter set is nevertheless able to retrieve the material model's hardening and softening behaviour with high accuracy (the mean deviation between predicted and measured forces is < 7%). The completion of the optimization run with its ~30 iterations on a state of the art workstation took little more than 21 hours.

4. MICROSTRUCTURE MODELING WITH SPATIAL RESOLUTION

In the examples shown so far, only JMAK models where used which do not take into account the spatial arrangement of grains and the orientation and neighborhoods of individual grains. Models for microstructure evolution with spatial resolution include cellular automata, Monte-Carlo-Potts, phase field models and vertex models. There is a vast amount of literature available dealing with the methods detailed above and their application to the simulation of dynamic and static recrystallization after hot working as well as SRX after cold working. The restrictions of the above-mentioned models for the simulation of a single deformation step and concurrent DRX or subsequent SRX have been investigated in depth in the past. Phase field modeling of SRX after hot deformation was recently analyzed by Güvenç et al. (2013, 2014), who used a crystal plasticity (CP)-FEM model to generate the input for the phase field simulation. The initial and deformed state of an RVE were simulated using the CP-FEM framework DAMASK developed at the MPIE Düsseldorf, Germany. The results of the CP-FEM are used as input to the phase field simulation to analyse the resulting evolution of the microstructure during SRX.

Although close, the grain morphology from the 2D simulation shown in figure 4 does not reproduce experimental findings precisely. If the simulation is performed with the goal that both the SRX kinetics and the grain morphology match the experiments, it is due to the lack of nucleation sites in 2D compared to 3D that this task cannot be accomplished. The SRX kinetics obtained from the phase-field simulation are also shown in figure 4. The experimentally obtained kinetics can be easily approximated by JMAK kinetics, but the phase field simulation gives only a rough approximation of the kinetics. Due to the large computation time of the phase field simulation even in the 2D case, there is no possibility to determine the parameters of the phase field model such as mobilities inversely. At present, it has to be stated that a full 3D simulation would be necessary to obtain more accurate results. Simulations by Zhu and Militzer (2012) with 3D phase field simulations were reported to match well with simulated results, showing that a 3D approach is indeed more suitable. However, the simulations were only performed for SRX after cold rolling, and solutions for recrystallization during and after hot working are still needed.

5. FEED BACK CONTROL AND MICROSTRUCTURE MODELING IN RING ROLLING

In FE simulation of ring rolling processes, the model must include the machine's closed-loop control system to achieve a realistic prediction of the process kinematics. The process holds at least eight degrees of freedom (figure 5). These degrees of freedom are adaptively adjusted by closed-loop control systems according to preselected control strategies and actual process variables (sensor values).

Until recently, in contrast to the actual process, most simulations of ring rolling processes were carried out based on kinematic data of all degrees of

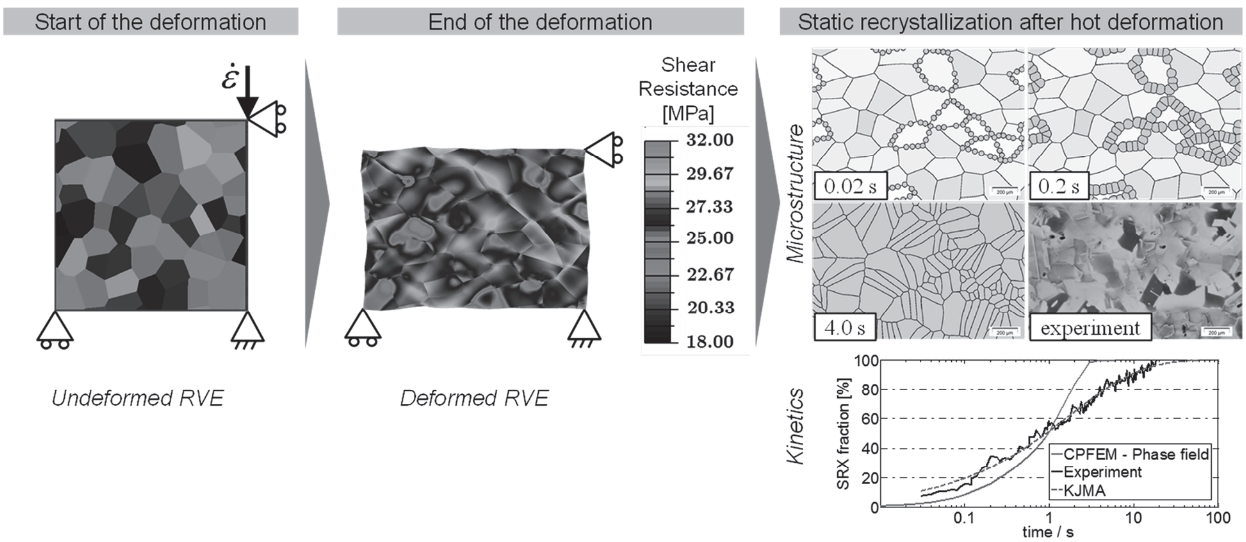


Fig. 4. Comparison of SRX kinetics and microstructure from experiment, CP-FEM-Phase Field and JMAK, after Güvenç et al. (2014).

freedom recorded from experiments. Simulations in the process layout stage are conducted using different simplifying approaches which can be found in literature cf. Li et al. (2008), Forouzan et al. (2003) and Wang et al. (2010). Since most of these approaches do not use the real ring rolling mill`s characteristics, deviations in predicting the process kinematics by simulation may occur. For an accurate process simulation in the layout stage, Jenkouk et al. (2012) integrated all sensors and actuators used in real ring rolling mills in an Abaqus/explicit FE model (figure 5). Also, parts of the technological controller CARWIN, which was provided by SMS Meer as a pre-compiled object file (black box to the user), were integrated. Due to the fact that the industrial control algorithms are unknown to the user, they cannot be adjusted for the development of new ring rolling strategies. Hence, as an alternative concept, a new control function was developed, cf. Hirt et al. (2014). In a self-designed controller, the initial parameters are entered in a Matlab GUI which is similar to the real ring rolling mill's interface. The tool motions are controlled based on the parameters and the machine limits in regard to actual roll power, torque and force during the entire simulation.

steps throughout the process. Therefore, only minor influences on rolling forces were found. Hence, the use of tabular flow stress values, determined in cylindrical compression tests leads to good correlation between experiment and FEA in calculated microstructure, rolling forces and material flow, respectively geometry (Henke et al., 2013).

Still, the approximation of boundary conditions is of high importance. Schwich et al. (2014) investigated the influence of boundary conditions on roll forces and geometrical values as well as on microstructure. Influences of transfer time from furnace to the ring rolling mill, emissivity, heat transfer and friction on the outer diameter, the maximum force, the force after 20 seconds and workpiece temperatures after rolling and a 300 second cooling period were examined. Therefore, a simulation study using a design of experiments (DOE) approach was conducted. Forming histories of one tracked point per simulation where compared (figure 6a) and a wide span of resulting forces was found (figure 6b). The transfer time was found to be the most influencing parameter whereas friction seemed to have minor influence on geometry as well as forces (figure 6c). Furthermore, influences on recrystallized fraction and grain size were examined. Throughout the process the grain sizes decreased from initial 120 μm to average grain sizes between approx. 18-38 μm at the end of the rolling stage. During the cooling period grain growth occurred. The average grain sizes grew to approx. 43-48 μm (figure 6d). Especially throughout the rolling stage strong influences of the transfer time on the grain size were identified. In the cooling period none of the examined parameters were identified to have significant influence (Schwich et al., 2014).

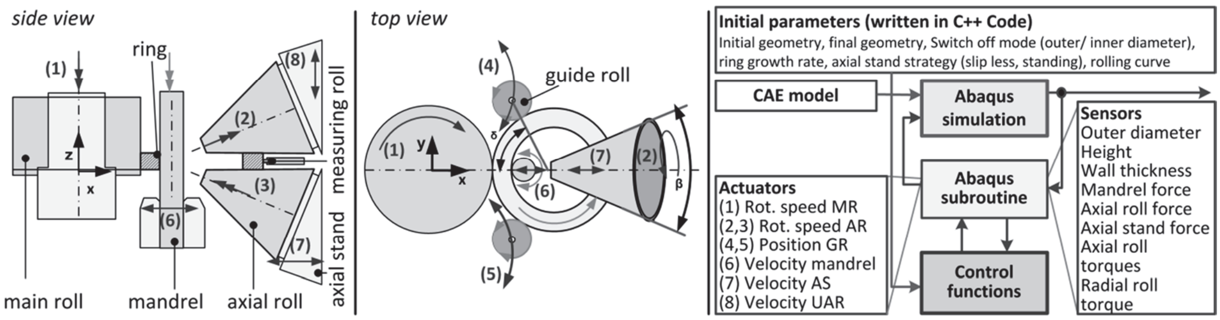


Fig. 5. Kinematics of a radial-axial ring rolling mill and structure of a controlled FE model, from Jenkouk et al. (2012).

However, the accuracy of FE simulations strongly depends on the input data. Especially the evolution of the workpiece's microstructure (grain size and recrystallized fraction) as well as the proper approximation of boundary conditions is of high importance. Postprocessing of tracked points with microstructure simulation can be used to predict the workpiece's final grain size and determine under which conditions recrystallization occurs during rolling. Henke et al. (2013) investigated the influences of dynamic and static recrystallization of an AISI 304 steel ring on rolling forces and geometry. Due to the comparatively slow SRX behavior of AISI 304, in this case static softening does only occur to a small extent between the deformation

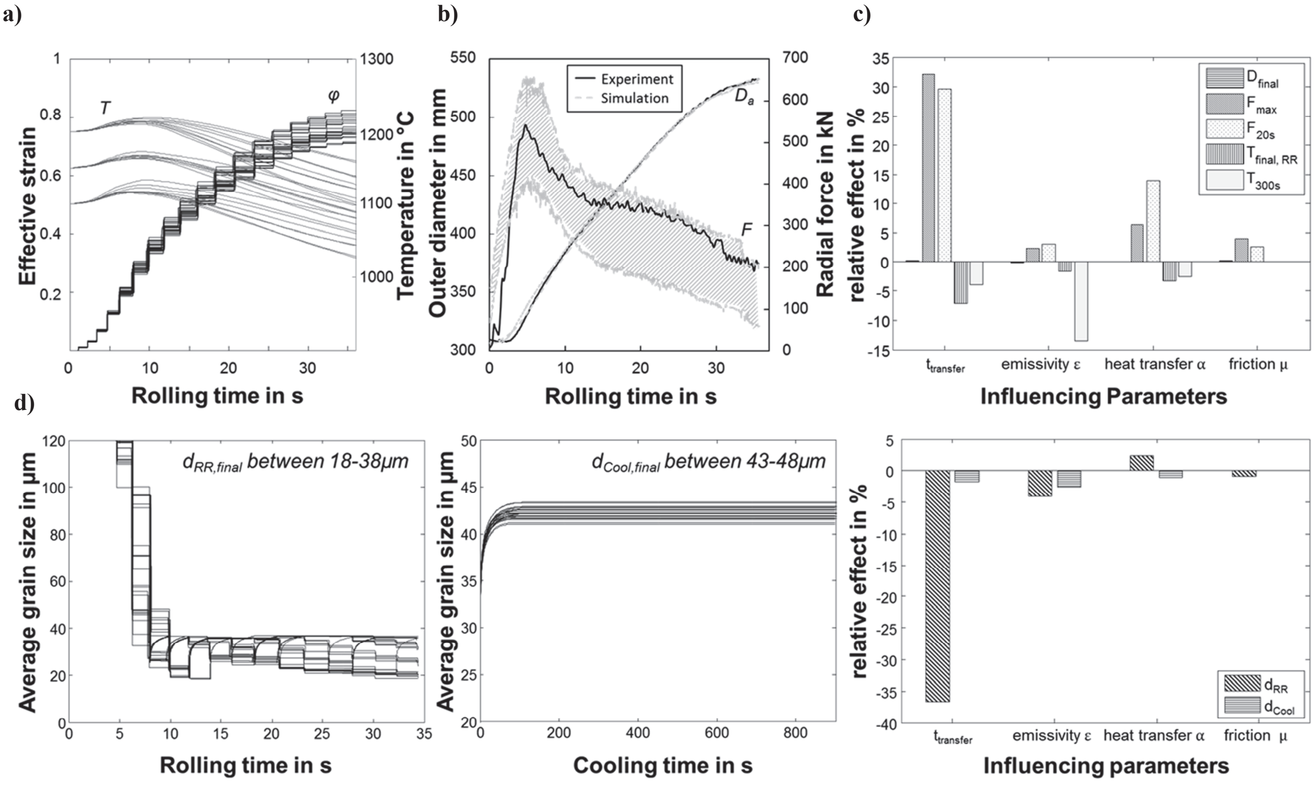


Fig. 6. Variation of input parameters and their effects on radial forces and geometry (a)-(c), effects of different boundary conditions on grain size during rolling and during cooling (Schwich et al., 2014) (d).

6. CONCLUSION

The results shown in this paper can be grouped into four kinds of coupled models: (i) coupled process and JMAK microstructure models (gear wheel), (ii) a fast rolling model coupled to optimization (plate rolling), (iii) a sequentially coupled model for deformation and static recrystallization on the micro-level and (iv) a process-control coupling for ring rolling. The examples show that the complexity of simulations of bulk metal forming processes increases, and the success of the simulations does not only depend on the accuracy of individual models such as the process and the material model, but also on their interaction and interplay with further models along the periphery of the process.

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REFERENCES

Forouzan, M.R., Salimi, M., Gadala, M.S., 2003, Three-dimensional FE Analysis of Ring Rolling by Employing Thermal Spokes Method, *International Journal of Mech. Sciences,* 45, 1975–1998.

Güvenç, O., Henke, T., Laschet, G., Böttger, B., Apel M., Bambach, M., Hirt, G., 2013, Modeling of Static Recrystallization Kinetics by Coupling Crystal Plasticity FEM and Multiphase Field Calculations, *Computer Methods in Materials Science*, 13, 368–374.

Güvenç, O., Bambach, M., Hirt G., 2014, Coupling of Crystal Plasticity Finite Element and Phase Field Methods for the Prediction of SRX Kinetics, *Steel Research International*, 85, 999–1009.

Henke, T., Hirt, G., Bambach, M., 2013, Application of a Material Model to Predict Rolling Forces and Microstructure during a Hot Ring Rolling Process, *Materials Science Forum*, 762, 354-359.

Hirt, G., Seitz, J., Schwich, G., Jenkouk, V., 2014, Aktuelle Entwicklungen zur Auslegung und Optimierung von Ringwalzprozessen, *21. Umformtechnisches Kolloqium Hannover*, 227-244.

Jenkouk, V., Hirt, G., Franzke, M., Zhang, T., 2012, Finite Element Analysis of the Ring Rolling Process with Integrated Closed-Loop Control, *CIRP Annals - Manufacturing Technology*, 61(1), 267-270.

Kawalla, R., Schmidtchen, M., 2013, Numerical Simulation of Hot Rolling, *Materials Science Forum*, 762, 22-30.

Li, L., Yang, H., Guo, G., Sun, Z., 2008, A Control Method of Guide Rolls in 3D-FE Simulation of Ring Rolling, *Journal of Material Processing Technology*, 205, 99-110.

Lohmar, J., Bambach, M., Hirt, G., Kiefer, T., Kotliba, D., 2014a, The Precise Prediction of Rolling Forces in Heavy Plate Rolling based on Inverse Modeling Techniques, *Steel Research International*, 85(11), 1525-1532.

Lohmar, J., Seuren, S., Bambach, M., Hirt, G., 2014b, Design and Application of an Advanced Fast Rolling Model with Through Thickness Resolution for Heavy Plate Rolling, *Proceedings of 2nd International Conference ICRF*, eds, Guzzoni, J., Manning, M., Milan, Italy, CD.

Lohmar, J., Bambach, M., Hirt, G., Kiefer, T., Kotliba, D., Jochum, M., Seuren, S., 2014c, Fast and Accurate Force Prediction for High Quality Heavy Plates by a State of the Art Rolling Model Calibrated from Mill Data via Inverse Techniques, *Proceedings of 1st European Steel Technology & Application Days* Paris, France, CD.

Schwich, G., Henke, T., Seitz, J., Hirt, G., 2014, Prediction of Microstructure and Resulting Roll Forces by Application of a Material Model in a Hot Ring Rolling Process, *Key Engr. Materials*, 622-623.

Seuren, S., Seitz, J., Krämer, A., Bambach, M., Hirt, G., 2014, Accounting for Shear Deformation in Fast Models for Plate Rolling, *Production Engineering*, 8, 17–24.

Sims, R. B., 1954, The Calculation of Roll Force and Torque in Hot Rolling Mills, *Proceedings of the Institution of Mechanical Engineers*, 168, 191–200.

Szeliga, D., Matuszyk, P., Kuziak, R., Pietrzyk, M., 2002, Identification of Rheological Parameters on the Basis of Various Types of Plastometric Tests, *Journal of Materials Processing Technology*, 125, 150-154.

Wang, Z.W., Fan, J.P., Hu D.P., Tang, C.Y., Tsui, C.P., 2010, Complete Modeling and Parameter Optimization for Virtual Ring Rolling, *International Journal of Mech. Sciences,* 52, 1325-1333.

Zhu, B., Militzer, M., 2012, 3D Phase Field Modelling of Recrystallization in a Low-Carbon Steel, *Modelling and Simulation in Materials Science and Engineering*, 20, 85011.

MODELOWANIE MATERIAŁÓW W PRZEMYSŁOWYCH, OBJĘTOŚCIOWYCH PROCESACH PRZERÓBKI PLASTYCZNEJ I ŁAŃCUCHACH PRODUKCYJNYCH

Streszczenie

Objętościowe procesy przeróbki plastycznej to zarówno procesy składające się z jednej operacji odkształcania, na przykład kucia w matrycy zamkniętej, jak i procesy składające się z kilku kolejno po sobie następujących operacji, na przykład proces walcowania na gorąco, proces walcowania pierścieni czy kucia w matrycy otwartej. Modelowanie numeryczne tego rodzaju procesów wymaga dokładnego ich opisu, w tym zastosowania odpowiednich modeli materiałowych. Należy podkreślić, że zmiany mikrostruktury podczas rekrystalizacji są w tym wypadku ważne, ponieważ mikrostruktura bezpośrednio przekłada się na wartość naprężenie uplastyczniającego i siły w procesie, a także decyduje o własnościach produktu. Ewentualne zmiany warunków procesu mają wpływ na zachowanie się materiału i ich uwzględnienie jest konieczne. Wymaga to metod pozwalających na jakościową ocenę niepewności oraz ich wpływu na wyniki modelowania. W pracy przedstawiono procesy, dla których zastosowano modele o różnych złożonościach i różnych skalach. Pierwszym przykładem jest kucie koła zębatego ze stopu 25MoCr4 w zamkniętej matrycy. Skomplikowany kształt kutej części wymagał użycia metody elementów skończonych i zastosowania modelu materiału uwzględniającego przemiany fazowe (JMAK). Drugim przykładem jest walcowanie blach, które można modelować w sposób uproszczony, wykorzystując rozwiązanie różniczkowego równania równowagi i uwzględniając naprężenie ścinające dzięki zastosowaniu meta modelu opracowanego na podstawie obliczeń MES. Tak zdefiniowanym modelem symulowano w krótkim czasie proces walcowania nawet długich przepustów, co pozwoliło na wykorzystanie modelu w zadaniach optymalizacji. Zjawisko rekrystalizacji dla stali wysoko-manganowych zachodzące pomiędzy przepustami walcowania na gorąco jest przykładem, gdzie model CP FEM, czy pola faz, są połączone w skali mikro. Dzięki temu możliwe było przewidywanie kinetyki rekrystalizacji z wykorzystaniem zmiennych o charakterze fizycznym, takich jak mobilność granicy ziarna. Z kolei dla walcowania pierścieni, aby otrzymać zgodną z rzeczywistością kinematykę procesu, model musi uwzględniać zamknięty system sterowania walcarką. Zdefiniowano osiem kinematycznych stopni swobody dla tego systemu (prędkości oraz położenia wszystkich rolek promieniowych, osiowych oraz pozycjonujących) poprzez zastosowanie wirtualnych sensorów zintegrowanych z modelem procesu. Przewidywanie końcowej wielkości ziarna oraz wyznaczenie warunków, w których zachodzi statyczna rekrystalizacja podczas sekwencji walcowania, otrzymano poprzez połączenie wyników modelu z wynikami symulacji mikrostruktury.

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