Quantification of uncertainties in grain size predictions of a microstructure-based flow stress model and application to gear wheel forging

T. Henke *, M. Bambach, G. Hirt (2)

Institute of Metal Forming (IBF), RWTH Aachen University, 52056 Aachen, Germany

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ABSTRACT

For reliable process design, full knowledge of the possible spread of the predicted target values such as grain size is desirable. In real production the spread of final product properties is caused by uncertainties in the processing conditions and the material behavior. This paper proposes a strategy which allows for incorporating the material behaviors uncertainties in a microstructure model. This model is applied to the design of a hot-forging process. It is shown that the probability distribution of the grain size value is asymmetric and predicts occurrences of grain sizes with a large deviation from the most probable grain size.

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1. Introduction

Hot-forged gear wheels are widely used, e.g. in drive systems of heavy-duty equipment. A possible process chain for gear wheel production by hot forging, case-hardening and milling operations is shown in Fig. 1. Shortening the process chain, e.g. by annealing directly from the forging heat to produce a ferrite–perlite microstructure suitable for milling or by increasing the carburizing temperature during case hardening could reduce both energy consumption and production costs [1] (cf. Fig. 1). Since the service performance of gear wheels crucially depends on the grain size, the hot forging process must yield a homogeneous, fine-grained microstructure. Abnormal grain growth after forging has to be avoided since a large grain size cannot be refined in subsequent process steps.
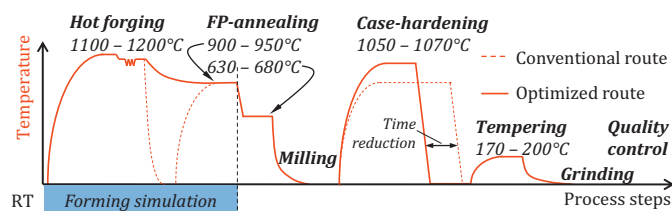

Fig. 1. Conventional and improved process chain for a bevel gear wheel.

For the design of hot working processes, finite element (FE) and material models are available which allow for the prediction of microstructure evolution due to recrystallization and grain growth (cf. Bariani et al. [2]). Applications of such microstructure models can be found in hot rolling [3] and hot forging [4].

However, for a robust design of the gear wheel forging process within an optimized processing route, a single deterministic FE

process simulation yielding a single value for the final grain size seems insufficient. Rather, full knowledge of the uncertainty of the predicted grain size seems necessary.

Both process conditions and material properties are subject to uncertainties. A number of methods such as sensitivity analysis, design of experiments and response surface methods are applicable for judging how sensitive the model output is to the variation of input parameters.

These methods are effective for analyzing the uncertainties in the model predictions that stem from process parameters such as initial workpiece temperature, and heat transfer coefficients.

However, the quantification of uncertainties stemming from microstructure evolution models is more involved. These models are highly nonlinear and non-smooth. Dynamic recrystallization, for instance, sets in instantaneously once the critical conditions are met. The evolution of grain size couples back on the microstructure evolution equations and on the flow stress, which makes grain size predictions potentially unstable.

The sources for uncertainties in a microstructure evolution model are manifold. The determination of the model parameters involves a series of tests, e.g. hot compression tests at various temperatures and strain rates and subsequent metallographic evaluation of the resulting microstructure. Uncertainties stem, e.g. from the material itself, the testing procedure, the non-linear regression performed to obtain the model parameters and from the metallographic determination of grain size and recrystallized volume fractions. Since it cannot be assumed that the uncertainties involved in the calibration of microstructure evolution models are normally distributed, resampling methods such as the Jackknife or Bootstrap method could be applied to estimate the probability distribution of the model parameters. Bootstrapping is a resampling method for simulating unknown statistics on the basis of a set of samples from which new virtual sample sets are generated by drawing with replacement [5]. Common problems of Bootstrap confidence intervals are bias and asymmetry. Also, Bootstrap confidence intervals can be rather large and hence predict rather unrealistic occurrences with a finite probability due to the fact that

* Corresponding author.

a single experimental result can be drawn several times during resampling [6].

In this paper, a modified resampling method is proposed to quantify uncertainties in a microstructure evolution model. The main difference to the Bootstrap method is that virtual data sets are generated without using individual experiments more than once. The resampling method is used to design a laboratory-scale gear wheel forging process using a new Niobium-alloyed 25MoCr4 case hardening steel such that a final target grain size of at most 16 μm is ensured. To analyze the applicability of the resampling method in practice, the experimental effort needed to quantify the uncertainties in the model parameters is studied. In addition, it is shown that the computational effort required to analyze the propagation of the uncertainties from the model parameters to the predicted grain size can be reduced by off-line simulations of microstructure evolution based on the thermo-mechanical history of each material point of interest. Hence, uncertainties in the processing conditions are neglected in this work since they can be decoupled from the uncertainties in the material model and handled using established methods such as sensitivity analysis or design of experiments (DoE).

The paper is organized as follows: In Section 2, an overview of the experimental and numerical work, i.e. the laboratory forging trials, materials characterization as well as the FE model and the model for microstructure and flow stress evolution is given. Section 2.4 details the proposed resampling strategy. Its application to results from the FE process simulation is presented in Section 3. The probability distributions of the final grain size in the forged gear wheel is estimated and compared to results from the laboratory forging experiments.

2. Experimental procedure, materials and methods

2.1. Material and testing

In this study, a recently developed micro-alloyed 25MoCr4 case-hardening steel with additions of Niobium (Nb) is used for bevel gear wheel hot forging trials. Its composition is given in Table 1. The motivation for micro-alloying with Nb stems from the desire to increase the carburizing temperature while maintaining a fine grain size (cf. Fig. 1), which is achieved by precipitates that cause pinning of austenite grain boundaries [1].

Table 1
Chemical composition of 25MoCr4 according to DIN 17210 (values are in wt.%).

Grade	C	Mn	Si	Cr	Mo
25MoCr4	0.23–0.29	0.60–0.90	0.15–0.40	0.40–0.50	0.40–0.50

The flow behavior and recrystallization kinetics of the 25MoCr4 steel were analyzed in the temperature range from 750–1200 °C and strain rates of 0.001–100/s using cylindrical compression tests. For each temperature and strain rate, five compression tests were performed to analyze the experimental uncertainties and to apply the proposed resampling strategy. All flow curves were compensated for deformation heating using a procedure detailed in [7]. The grain growth kinetics were analyzed by annealing tests at temperatures between 1000 and 1200 °C. The samples were quenched after annealing and analyzed metallographically. At temperatures above 1100 °C abnormal grain growth was observed. Compared to a conventional Al-micro-alloying concept fine grain stability is increased by approximately 150–200 °C.

2.2. Laboratory-scale gear wheel forging

A tool stack consisting of a single closed cavity was designed for laboratory hot forging experiments of the bevel gear wheel. The process sequence consists of the pre-heating of the billet, transfer to the die stack, dwelling in the lower die, closing the cavity with the upper die, filling the cavity by pushing the knock off while keeping the cavity closed, dwelling of the forged gear wheel in the lower die, transfer of the forged gear wheel and the first phase of FP-annealing (cf. Fig. 1). Downstream processing has been examined in [1] and is not addressed in this paper.

2.3. Finite element and material model

FE simulations of the forging process were conducted using the FE-code Deform 3d^{TM} according to the individual process steps detailed in the previous section. The dies were modeled as rigid bodies. Due to the symmetry of the gear-wheel only one tooth (1/16 of the gear-wheel) was considered. It was meshed with 52k tetrahedral elements. The process conditions and boundary conditions are summarized in Table 2.

Table 2
Processing conditions and boundary conditions for the FEA.

Pre-heating temperature	1200 °C for 20 min
Transfer time furnace – tool stack	15 s
Dwell time on lower die	1 s
Forging velocity	25 mm/s
Annealing temperature	900 °C
Friction factor	0.5
Transfer time tool stack – furnace	15 s
Heat transfer coefficient	15,000 W/m^2/K
Radiation coefficient	0.8
Convection coefficient	20 W/m^2/K

To model the flow behavior and microstructure evolution, equations based on the work of Luton and Sellars [8] were adopted, see Table 3. The flow curves are modeled via characteristic points such as the peak strain and stress, which are expressed as a function of the Zener–Hollomon parameter, $Z = \dot{\varepsilon} \cdot \exp(Q_w/RT)$. Q_w and Q_{GG} are the activation energies for hot deformation and grain growth, p_1, ..., p_{18} are model parameters. The model is implemented in such a way that generations of recrystallized volume fractions are treated independently. They are represented by their own grain size, hardening state, etc. and stored in a tree-structure [9]. The index 0 refers to the unrecrystallized material. The index i of the recrystallized volume fraction X_i, the effective strain ε_i, the flow stress σ_i and the grain size d_i indicates that volume fraction i has undergone i recrystallization cycles. The flow stress is obtained by a linear rule of mixture from the individual volume fractions, Eq. (5).

Table 3
Semi-empirical model to describe coupled evolution of flow stress and microstructure, i.e. grain size.

Flow stress of fraction i **(1)** $\sigma_i = \sigma_p \left[\frac{\varepsilon_i}{\varepsilon_p} \cdot \exp\left(1 - \frac{\varepsilon_i}{\varepsilon_p}\right) \right]^{p_1}$	Peak strain **(2)** $\varepsilon_p = p_2 \cdot d_0^{p_3} \cdot Z^{p_4}$
Maximum flow stress **(3)** $\sinh(p_5 \cdot \sigma_p) = p_6 \cdot Z^{p_7}$	Steady-state strain **(4)** $\varepsilon_{ss} = p_8 \cdot d_0^{p_9} \cdot Z^{p_{10}}$
Rule of mixture **(5)** $\sigma = \sigma_0 \left(1 - \sum_{i=1}^{n} X_i\right) + \sum_{i=1}^{n} \sigma_i X_i$	Critical strain **(6)** $\varepsilon_c = p_{11} \cdot \varepsilon_p$
DRX kinetics **(7)** $X_i = 1 - \exp\left(p_{12} \cdot \left(\frac{\varepsilon_i - \varepsilon_c}{\varepsilon_{ss} - \varepsilon_c}\right)^{p_{13}}\right)$	Dyn. recrystallized grain size **(8)** $d_i = p_{14} \cdot Z^{p_{15}}$
Grain growth **(9)** $d_{GG} = \left(d_0^{p_{16}} + p_{17} \cdot t \cdot \exp\left(\frac{-Q_{GG}}{RT}\right)\right)^{1/p_{18}}$	

2.4. Model calibration and resampling

The flow stress and microstructure evolution model detailed in Table 3 is defined by a set of coupled non-linear equations. Parameter identification for this model is essentially a regression problem. Using a set of experimental data, a least squares