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On instabilities of force and grain size predictions in the simulation of multi-pass hot rolling processes

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ABSTRACT

In multi-pass rolling processes such as plate rolling, accurate predictions of roll force and torque over all roll passes are desired, so that the pre-calculated roll pass schedule can be put into practice without exceeding the limits of the roll stand. In this context, the grain size has two roles; the final grain size determines the product properties, and the evolution of grain size influences the force predictions. Since the grain size predicted after each roll pass enters the recrystallization kinetics and grain size evolution equations of the subsequent pass, a feed-back loop for the grain size calculation is created, which may become unstable so that the computed roll force and grain size become very sensitive to small variations in the input parameters. Although models for the evolution of grain size in multi-stage hot rolling have been applied in the industry for decades, their mathematical stability has not been given much attention, which poses difficulties for force and grain size predictions in cases subject to partial recrystallization. In this paper, the stability of a common semi-empirical model for static recrystallization and grain growth is investigated. The conditions under which instabilities occur are analyzed both for an industrial plate rolling pass schedule and for idealized load cycles. It is shown that complete recrystallization between roll passes leads to a stable grain size evolution, and that some states of partial recrystallization are unstable and hence problematic for force and grain size predictions. Instabilities in force and grain size predictions of an industrial pass schedules are analyzed by computing sensitivities using automatic differentiation of the model, showing that large amplification factors may occur if the states of partial recrystallization are treated by average strains and grain sizes. The instabilities are an inherent property of the closed-form equations for microstructure evolution for some states of partial recrystallization. However, the side effects of the instabilities can be reduced if the microstructure is not represented by average values of grain size and accumulated strain but by substructures generated by partial recrystallization. This way, the accuracy of roll force predictions can be considerably improved.

1. Introduction

The numerical simulation of industrial hot rolling processes has been subject to research for many decades. On the one hand sophisticated approaches have been developed which couple models on all scales from the product's microstructure level up to the elastic behavior of the roll stand. These models are used off-line, in the development of new materials or equipment, and are nowadays summarized under the umbrella term 'integrated computational materials engineering' (ICME). On the other hand, simplified but fast models are used for pass schedule calculations and on-line process control. A large number of models in the technical literature allows for the simulation of multi-pass hot rolling processes including microstructure evolution. Due to the fact that the evolution of microstructure and flow stress are strongly coupled, it appears necessary to take the microstructure evolution into account whenever multiple passes are considered, not only in cases where the final microstructure and properties shall be predicted, but also when global process variables such as roll force and torque are computed.

Evolution equations for the microstructure may be simple closed-form equations or full-scale microstructure evolution codes with spatial resolution such as the phase field method. Recrystallization and grain growth, which are the main mechanisms that change the microstructure during hot rolling, manifest themselves

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as changes in the austenite grain size in the first place. During cooling, the transformation to ferrite or ferrite–perlite is affected by the austenite grain size, hence the austenite grain size present after hot rolling has a decisive influence on the product properties. An accurate prediction of grain size evolution is also important when the roll force is computed based on flow stress models that draw upon the current grain size and recrystallized volume fraction.

However, whenever grain size evolution is calculated over many passes, as it is the case in hot rolling process chains, a feedback loop is created since the grain size predicted after each pass and subsequent interpass time influences the recrystallization and grain growth kinetics after the following pass. Hence, a thorough analysis of the conditions that lead to unstable grain size predictions is mandatory. Although models for the evolution of grain size in multi-stage hot rolling processes have been developed and employed over more than four decades, the stability of grain size and recrystallization models has not been given much attention in the past.

For the models that are in use in the industry nowadays, is seems important to provide a thorough analysis of instabilities that may occur. Also, methods to predict instabilities are needed, and approaches must be found to prevent that the instabilities affect the accuracy of the force and grain size predictions.

The structure of this paper is as follows: In Section 2, existing literature on modeling of microstructure and grain size evolution in multi-pass hot rolling processes is reviewed, with a strong focus on semi-empirical models for hot rolling of steel and on the discussion of the stability of the model predictions. Since instability will be shown to be caused by partial recrystallization, the treatment of partially recrystallized states will be discussed. Also, a brief introduction to dynamical systems and the stability of fixed-point iterations is given. In Section 3, a process model for plate rolling and a specific microstructure model proposed by Beynon and Sellars (1992) for the simulation of grain size and roll force is introduced and applied to an industrial roll pass schedule for a Cr-Mo steel. The stability of the grain size evolution and force predictions for the industrial roll pass is analyzed in Section 4. Sensitivities of the roll force and grain size predicted by the model are computed using the method of automatic differentiation of the simulation code. In Section 5, the stability of the model equations is analyzed by stability maps, which evaluate the stability based on the Jacobian matrix of the evolution equations for the grain size and accumulated strain along the roll pass schedule. Besides that, stability of the model equations is also investigated from a theoretical point of view using idealized deformation passes, showing that bifurcation and chaotic evolution occur for some states of partial recrystallization. Finally, in Section 6 it will be shown that the force predictions can be improved in spite of the instability of the model equations for some states of partial recrystallization if the microstructure is not represented by a single average value of grain size and accumulated strain but by substructures created by partial recrystallization, which are characterized by individual state variables.

2. Review of previous work on grain size prediction in hot rolling, sensitivity analysis and stability

2.1. Modeling of grain size evolution and recrystallization in rolling processes

Comprehensive reviews of microstructure evolution models for metal forming were given, e.g., by Bariani et al. (2004) as well as Lenard et al. (1999). Since the present work focuses on instabilities in multi-pass hot rolling, microstructure models that were developed for simulating hot rolling pass schedules will be reviewed in this section, focusing on the role of grain size in terms of the creation of feed-back loops and the discussion of possible instabilities.

Substantial developments on the modeling of microstructure evolution along hot rolling process chains for steel and aluminum sheet production were made by Sellars and various co-workers. Early work on modeling of recrystallization and grain growth in hot rolling was published by Sellars and Whiteman (1979), who considered plate rolling of C-Mn steel. The model equations for recrystallization draw upon the Zener–Hollomon parameter,

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \tag{1}$$

The kinetics of static recrystallization (SRX) are modeled using a modified JMAK equation due to Kolmogorov (1937), Johnson and Mehl (1939) and Avrami (1939) who studied the kinetics of phase transformations:

$$X = 1 - \exp\left(\ln(1-0.95)\left(\frac{t}{t_{95}}\right)^2\right) \tag{2}$$

In contrast to the original equation, the time t was replaced by Sellars and Whiteman (1979) by the temperature-compensated time

$$W = \begin{cases} t \exp\left(\dfrac{-480,000}{RT}\right) & \text{for constant temperature} \\ \sum t_i \exp\left(\dfrac{-480,000}{RT_i}\right) & \text{for changing temperature} \end{cases} \tag{3}$$

to account for the effect of temperature changes. The time for 95% SRX is given by

$$t_{0.95} = 3.54 \times 10^{-21} \varepsilon^{-4} d_0^2 Z^{-3/8} \exp\left(\frac{480,000}{RT}\right) \tag{4}$$

for a C-Mn steel. The recrystallized grain size is

$$d_{rex} = 25\left(\frac{1}{6.7\times10^{-2}} \ln\left(\frac{Z}{8.5\times10^{9}}\right)\right)^{-2/3} \varepsilon^{-1} d_0^{1/2} \tag{5}$$

and finally, grain growth is modeled by

$$\begin{aligned} d^{10} &= d_0^{10} + 5.02\times10^{53} t \exp\left(-\frac{914,000}{RT}\right) \quad T < 1000^\circ C \\ d^{10} &= d_0^{10} + 3.57\times10^{32} t \exp\left(-\frac{400,000}{RT}\right) \quad T > 1000^\circ C \end{aligned} \tag{6}$$

The initial grain size is denoted by d_0 while d_{rex} and d represent the grain size after recrystallization and grain growth, respectively. With their model, Sellars and Whiteman (1979) consider multi-pass hot rolling and recognize the importance of analyzing the influence of uncertainties in the model constants. For the roll pass schedule they consider, however, they conclude that the effect of uncertainties is 'self-compensating', i.e., smaller amounts of recrystallization in one pass will lead to larger recrystallized fractions in the subsequent one so that the effect of uncertainties is compensated over the passes. Sellars and Whiteman (1979) also show that changes in the roll pass schedule lead to major changes in the final microstructure. Comparisons with experiments were reported to be in good agreement, but it was pointed out that the calculations are sensitive whenever the interpass times are in the same order as the recrystallization times.

Seven years later, Sellars (1986) published another paper on modeling microstructure evolution in hot working processes. The model equations in this work cover also dynamic recrystallization (DRX), but DRX is not considered in the final model implementation. Multi-stage plane strain compression tests are performed to validate the proposed model. The model equations for static recrystallization and grain growth are essentially the same as those in