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# Investigation of the influence of the chemical composition of HSLA steel grades on the microstructure homogeneity during hot rolling in continuous rolling mills using a fast layer model

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**Abstract.** The newly developed LaySiMS simulation tool provides new insight for inhomogeneous material flow and microstructure evolution in an endless strip production (ESP) plant. A deepened understanding of the influence of inhomogeneities in initial material state, temperature profile and material flow and their impact on the finished product can be reached e.g. by allowing for variable layer thickness distributions in the roll gap. Coupling temperature, deformation work and work hardening/recrystallization phenomena accounts for covering important effects in the roll gap. The underlying concept of the LaySiMS approach will be outlined and new insight gained regarding microstructural evolution, shear and inhomogeneous stress and strain states in the roll gap as well as local residual stresses will be presented. For the case of thin slab casting and direct rolling (TSDR) the interrelation of inhomogeneous initial state, micro structure evolution and dissolution state of micro alloying elements within the roughing section of an ESP line will be discussed. Special emphasis is put on the influence of the local chemical composition arising from direct charging on through-thickness homogeneity of the final product. It is concluded that, due to the specific combination of large reductions in the high reduction mills (HRM) and the highly inhomogeneous inverse temperature profile, the ESP-concept provides great opportunities for homogenizing the microstructure across the strip thickness.

## 1. Introduction

During the past three decades simulation of metal forming processes has become a necessary tool for quality insurance, automation and the development of new materials technologies. Especially the



demands of thermo-mechanical treatments considering the interaction of process entities such as temperature, stress and strain state on the one hand and the dependencies of microstructure developments during hot rolling on the other require numerical tools which are able to describe these complexly interrelated properties accordingly. In hot rolling applications the material flow is simulated with different approaches and models. Overviews of the concepts, differing in the computing effort necessary and used modelling depth, are given in [1-3].

One of the key issues is a proper choice of the modelling approach for stress and strain state, which can range from involvement of all components of the strain and strain rate tensor to the assumption of parallelepipedic deformation. Nowadays Finite Element methods, boundary approaches or slab theory are used. As a rule of thumb the accuracy and complexity of the obtained strain rate and stress tensor scales insures the computational effort to be done. Depending on the field of application the used modeling approach usually lies somewhere in between these methods [2].

To combine the advantages of a higher modelling depth with a fast end flexible solution procedure an improved layer model, based on slab theory has been developed [4-7]. The model was first developed and tested as a symmetric model and is now extended to general asymmetric rolling conditions. Thereby asymmetries in relation to roll gap geometry, tribology, initial material state and temperature distribution are taken into consideration. Residual stresses are also available.

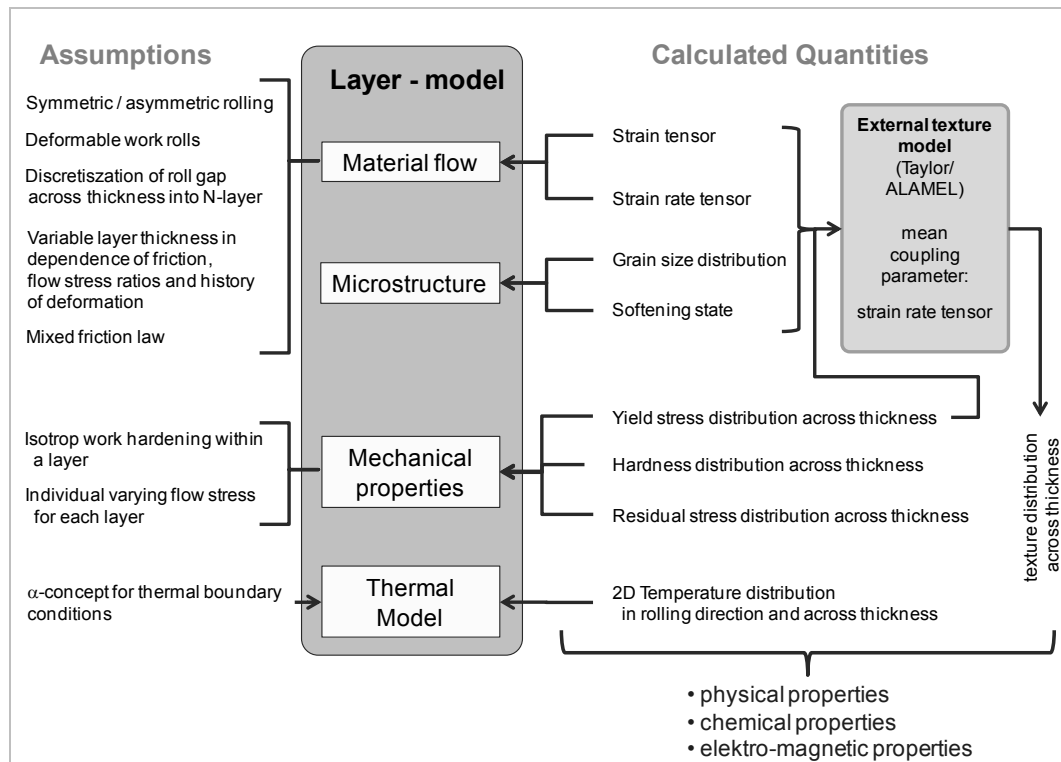
In the following a short overview of the main features and models included is given. For selected examples of hot rolling tasks a comparison to Finite Element computations is shown. In relation to rolling schedules for TSDR or ESP-concepts the effect of an inhomogeneous temperature distribution on local chemical compositions and strain states is discussed.

## 2. Model description

The basis of the new general N-layer asymmetric rolling model "LaySiMS" was described earlier in [4-6]. Regarding the inhomogeneous deformation state in the roll gap as well as the temperature gradient, the strain, strain rate and the hardening and softening, which are inhomogeneous across the thickness, can be calculated. The simulation model consists of four sub models: material flow model, mechanical properties, thermal model and microstructure model, see Fig. 1. The assumptions and simplifications of the layer model are summarized in the Figure as well. In Fig. 1 the calculated quantities are also indicated. The model of material flow is based on an extended strip theory and simplified thermal computations [5, 6]. The roll gap is divided into N – layers along the y-direction (direction perpendicular to the rolling direction). Within the computation,  $h_i$  are the thicknesses,  $\vartheta_i$  the temperature,  $\sigma_{Fi}$  the flow stress and  $v_{wxi}$  the velocity of each individual layer. Interfaces between the layers as well as the friction coefficients  $m_i$  are numbered beginning at the top of the strip. The roll gap length is given by  $L_d$ . Back and forward tension is indicated with  $\sigma_R$  and  $\sigma_V$ . At the neutral line  $x_{Ni}$  the flow speed of the material is equivalent to the horizontal speed of the rolls  $v_{wxi}$  or a value in between, fulfilling the requirements of mass balance. Within the model dissimilar radii of the work rolls  $R_1$  and  $R_2$  were used. Flattening of the work rolls is considered using the approach of Hitchcock [1, 2].

The changes in thickness of each layer will be followed individually along the rolling direction. Due to the possibility of a high number of individual layers, inhomogeneous deformation states can be approximated using viscoplasticity methods. Incompressibility is guaranteed due to the application of volume constancy in all layers, starting with corresponding velocities for each individual layer in the neutral line. The basic equations for plastic and elastic deformation of the layers were derived in a similar way as described in [1, 2]. The yield criterion of v. Mises and an analytic description of the roll gap geometry were used. In addition, there is a need for an additional semi empirical equation, which describes the thickness variation of each individual layer during the deformation process. For this purpose, the model of Zhang for two layers [6] was modified for an application in N-layer configurations with arbitrary hardness and thickness distributions. The layer thickness model depends on ratios of local yield stresses of each layer, friction, layer thickness ratio as well as the strain history of the individual layer.

The material flow model is based on the data of the stress-strain-behaviour of the used material as function of the deformation, deformation rate, and temperature. Within the model a mean yield stress of the layers is used, which is determined by a recursive approach using a linear rule of mixing to compute the resulting rolling force and torque. For each individual layer the yield stress can be determined from different yield stress approaches, which are semi-empirical models after Hensel and Spittel [5], Li et. al. [9], mean flow stress approaches of Misaka-Minami [13] or phenomenological models e.g. after Engberg et. al. [16].

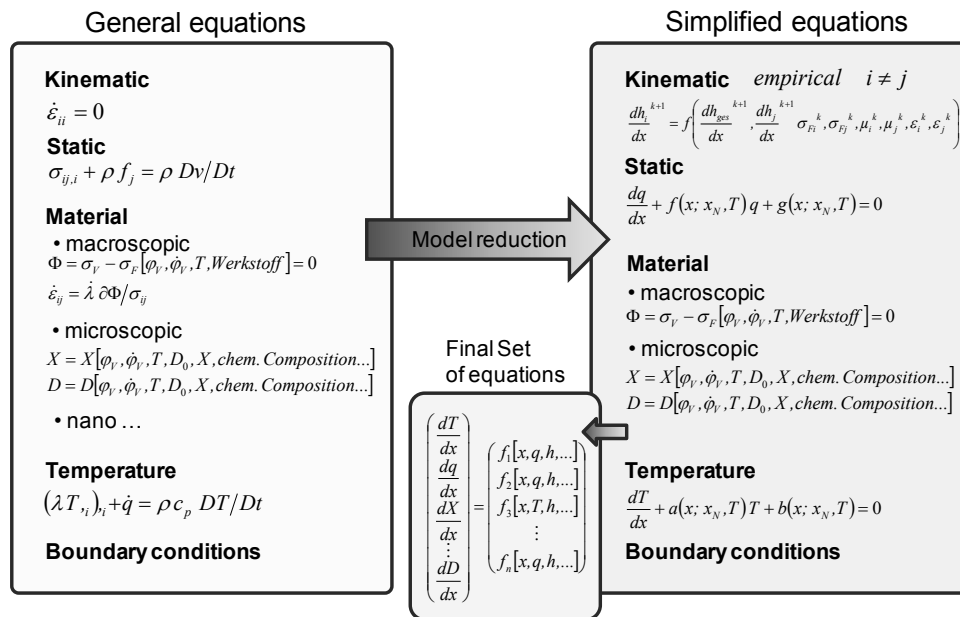


**Figure 1.** Description of the model [17].

The dynamic and static softening is included in the simplest version using a modified JMAK-Model which was described in [8-13]. The model takes into consideration the retarding effect of microalloying elements. In the initial model approach described by [14] the dissolute content was predicted using solubility products. For a more detailed investigation of the substructure development in steel grades an approach based on Engberg and Lissel [16] was also implemented. The computational results given here are based on a version of LaySiMS using thermodynamical computations based on MATCALC [15]. Therefore an interface between LaySiMS and MATCALC was implemented which allows for automated computations of the dissolution state or precipitation kinetic for real chemical compositions.

During computation, an equivalent plastic strain is required. It is given by the actual deformation state itself and two additional terms arising from shear at the entrance region  $\Delta\varphi_{vorEi}$  [1, 2, 6, 7] and from the prestrain  $\Delta\varphi_{eff i}$  of the former deformation step. The temperature evolution was computed using a quasi 1D-heat conduction equation for each layer taking convective terms into consideration [5, 6]. In general, all thermal equations are coupled to deformation by a dissipative term. The mechanical properties across the thickness are calculated based on the description of the material flow and the flow curves of the material.

Due to the assumptions and simplifications made a stiff set of first order differential equations has to be solved, Fig. 2, which strongly depends on several internal parameters especially the individual position of the neutral line  $x_{Ni}$  for each layer. In general, a numerical solution has to be found by imposing an iteration for finding the neutral zone position  $x_{Ni}$ . The program package implemented is based on the computer algebra system MATHEMATICA.



**Figure 2.** Scheme for complexity reduction of the full model towards the simplified layer-based model with minor sacrifice of accuracy and large reduction of computational effort [17].

The final result will be obtained within an iterated approach: First, a numerical solution of the thermal mechanical problem including the layer thickness distribution is obtained using the simplified homogeneous strain state and position of neutral line of the classical slab theory. The plastic deformation starts and ends at the same position for each layer [17]. After determining the new strain state and the improved position of the neutral line, the real material flow, the temperature distributions as well as the microstructure evolution due to dynamic softening are calculated in a second step. The third step includes the computation of the final stress and strain state from the condition of local constancy of volume flux for each layer, using the predicted strain, strain rate and temperature distributions which results in a shift of the initial positions where the plastic deformation starts or ends, mostly toward the centre of the roll gap. To obtain the shifted positions, residual stresses for each layer have to be introduced at the entrance and exit of the roll gap. Starting from the neutral line, the volume constancy conditions for each layer together with a force balance give a set of equations from which the residual stresses can be deduced.

Due to the simplified structure of the equations the whole solution for one deformation step can be found within a fraction of seconds, depending on the number of layers used for discretization [6, 7]. A detailed description of the model as well as several comparative studies will be published elsewhere [7].

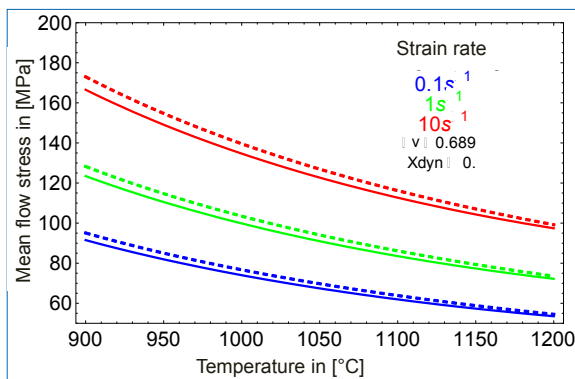
### 3. Application to hot rolling

Within an extensive comparative study the new layer model was tested in relation to analytical solutions, Finite Element computations and experimental investigations [7]. Temperature distribution, microstructure evolution and strain state agree well with results from generally accepted numerical and analytical methods as well as experiments. The accuracy of the microstructure evolution is well

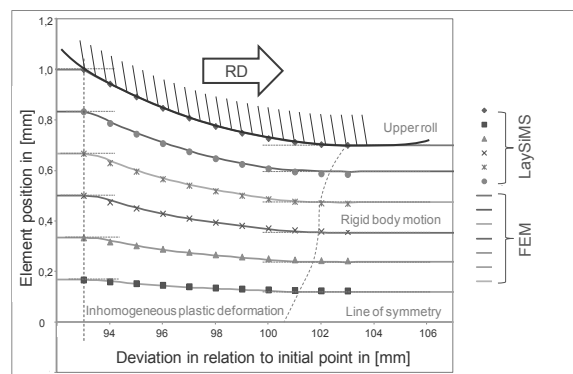
satisfying but, of course, depends strongly on the applied constitutive model. In the mentioned investigations the accuracy checks were performed with microalloyed HSLA steel grades. Further experimental trials were performed and compared to the model for a more general assessment of the performance of LaySiMS. As an example for the accuracy of the predicted strain state in Fig. 4 the tracking lines of the knots of an FE computation and the layer distribution computed by LaySiMS are given. The tracking lines agree well but the computational time of LaySiMS was more than thousand times faster than MSC.MARC which was used for the FEM trials.

The application of LaySiMS to different rolling technologies gave a clear understanding of the local material behavior during hot rolling. Due to the model approach the material can be followed along fixed tracking lines through the whole rolling mill without any intermediate homogenization or other additional simplifications. The differences are clearly visible in Fig. 6 for similar rolling schedules, which differ in the initial temperature distribution only. Due to a high equivalent strain within the first rolling steps and an inhomogeneous temperature distribution with largest temperature values in the strip core a strain distribution with increased homogeneity is reached. Fig. 7 shows the homogenization of strain distribution across the strip thickness for rolling conditions equivalent to the roughing section of an ESP mill. The temperature distribution corresponds to Fig. 6a.

In both cases of Tab. 1 and Fig. 3 and 5 three forming steps were necessary to reduce the microstructural inhomogeneity. In these cases a change in dissolution state is more significant for a softening behaviour than for the mean yield stress. Due to the retarding effect of the dissolved micro alloying elements, a static or metadynamic softening during the transport between the first stands can be used to avoid unwanted grain growth caused by the high temperatures at this process stage.



**Figure 3.** Influence of dissolution state on mean flow stress after Miska-Minami [13] (dashed lines: nominal composition given in Tab.1).

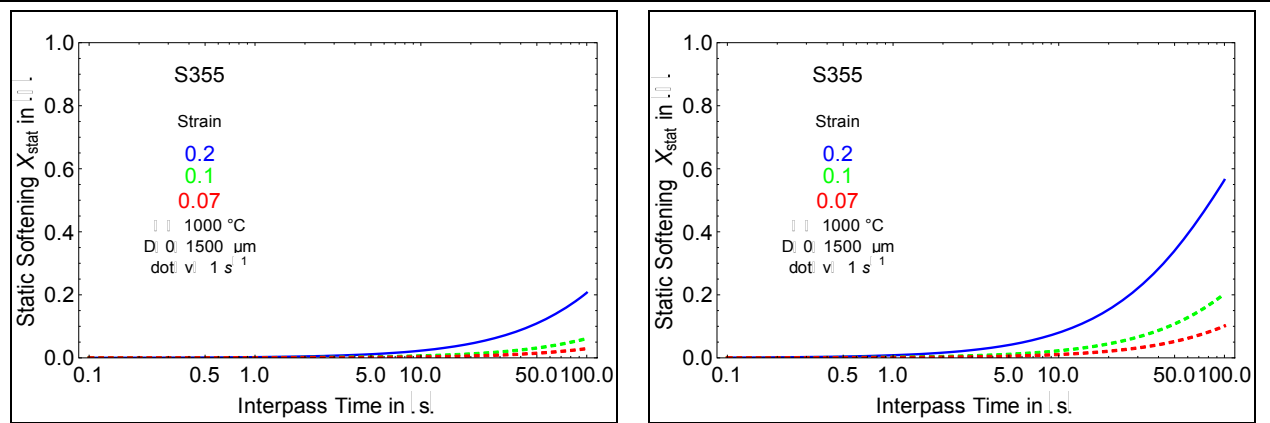


**Figure 4:** Comparison between the track lines of FE knots and LaySiMS layer computation (RD- rolling direction) [17].

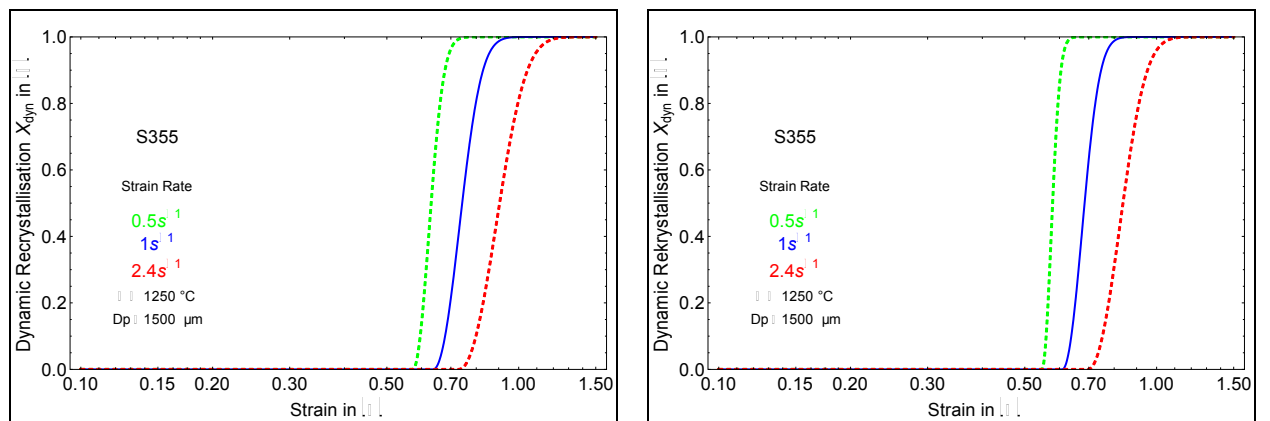
**Table 1.** Influence of chemical composition on recrystallization kinetics (model approach after [14]), equilibrium dissolution state from MATCALC computations

Nominal chemical composition	Equilibrium dissolution state
Dissolved content of microalloying elements in S355	
{ wtNb, wtTi, wtV, wtMo }	{ wtNb, wtTi, wtV, wtMo }
{0.0423, 0.0028, 0.0336, 0.097}	{0.00213004, 0.000046024, 0.0335575, 0.096999}

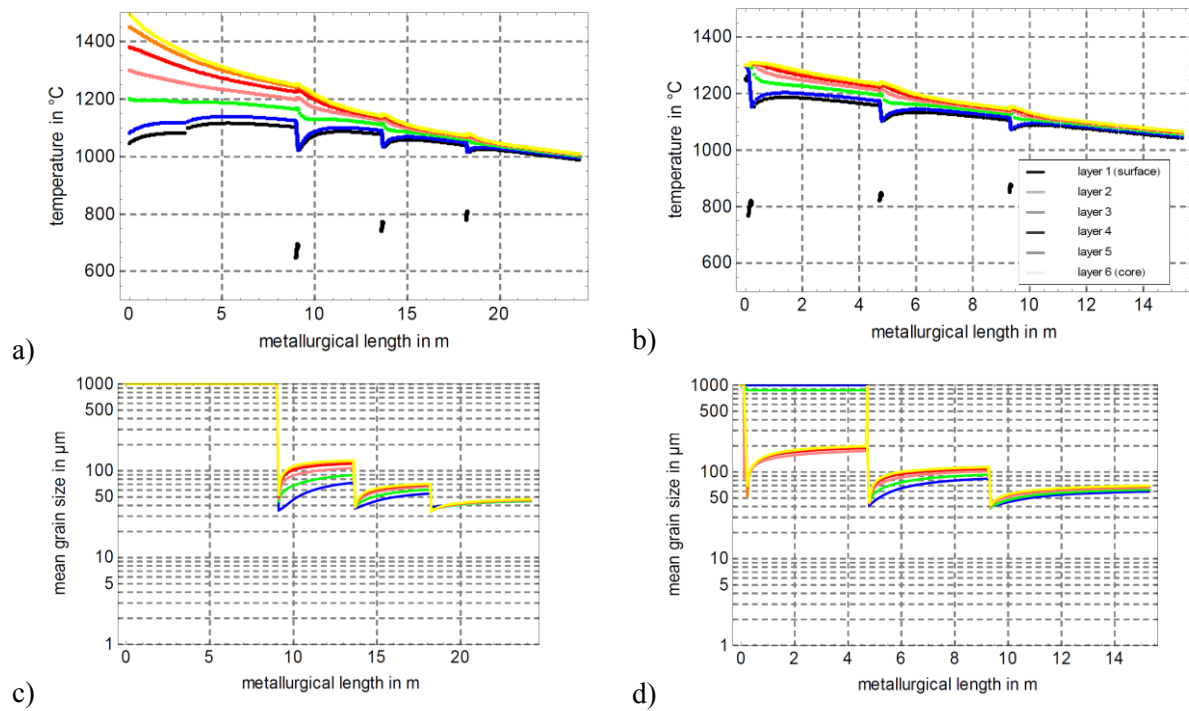
Static softening



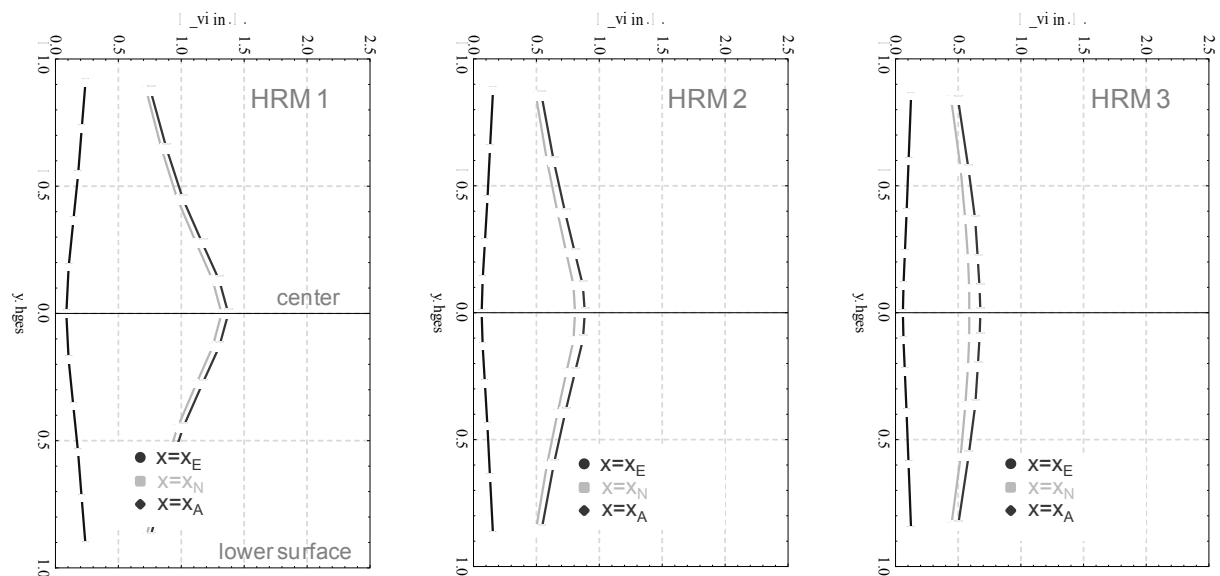
Dynamic recrystallization



**Figure 5.** Softening kinetics of HSLA S355 and their dependence on chemical composition (model approach of [14])



**Figure 6.** Temperature and mean grain size distribution of S355 along the metallurgical length in the layers after the roughing section with different initial temperature distributions: left (a,c) - inhomogeneous, right (b,d) - homogeneous; for computation an symmetric 11 layer configuration were used [17].



**Figure 7.** Homogenization of equivalent strain distributions during rolling in a roughing section with inhomogeneous initial temperature distributions (computation with a symmetric 11 layer configuration;  $x_E$ ...exit region,  $x_A$ ...entrance region,  $x_N$ ...neutral line).



#### 4. Conclusions

For accomplishing accurate and thorough analysis of hot rolling processes within reasonable times a large modelling depth at a minimal computational time is demanded when the focus is on gaining reliable information regarding inhomogeneous material evolution. To meet these concurring requirements, a fast simulation method for hot rolling was developed. The computation of the local strain state under consideration of the material evolution processes was performed using the Mathematica-based program package *LaySiMS*. Depending on the number of layers, an inhomogeneous strain state in the roll gap can be approximated with sufficient accuracy at reasonable computation times. Further refinement of results can be achieved by either increasing the number of equidistant layers or introducing layers of different initial heights for local refinement in regions of highest interest accounting for a higher resolution in areas of significant local gradients. A comparison of computational results calculated with the layer model with those resulting e.g. from FE calculations correspond well. Hence, the benefit achieved by using the *LaySiMS*-system is a dramatically reduced computational time by keeping the necessary modelling depth and accuracy.

#### 5. Acknowledgments.

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