Calculation of the microstructural evolution and of the mechanical properties for hot rolling of steels

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Industrial application examples for plate, strip and beam rolling as well as for thin slab rolling reveal a sufficient accuracy of a metalphysically- based model for describing the microstructural evolution during hot rolling of unalloyed weldable structural steels. The current development stage justifies the transition from off-line to on-line application of microstructure models.

INTRODUCTION

The combination of rolling schedule calculations including rolling forces and torques with calculations of the microstructural evolution during hot rolling of flat products has been described in /1-3/. Microstructural models are applied to an increasing extent both in the operation and the design of hot rolling mills for quality assurance purposes and for the further development of rolling processes (**Figure 1**). The objective of the paper is to indicate the suitability of such a metalphysically based model for the rolling of plates, strips and beams from unalloyed weldable structural steel grades.

ALGORITHMS

The basic for the determination of yield strength and tensile strength is the calculation of the microstructural evolution in the austenite and of the mean ferrite grain size d_α in dependence on the rolling technology and the cooling regime after the finish rolling (**Figure 2**).

The microstructural evolution of the austenite from pass to pass can be calculated by means of the algorithms proposed by C.M.Sellars and J.A.Whiteman /4/ as well as by C.M.Sellars and J.H.Beynon /5/ (**Table 1**). These algorithms were tested for multiple pass hot rolling of a continuously casted unalloyed weldable structural steel and have shown a sufficient accuracy for practical purposes /3,6,7/. The deformation of uncompletely recrystallized austenite can be described according to P.B.Choquet et al. /8/.

An effective austenite grain size for the entrance in the following pass is calculated from the grain size of the unrecrystallized and of the recrystallized fraction of the austenite. The calculation of the microstructural evolution is explained in more details elsewhere /6/. The computer program in

Figure 3 permits the simulation of any hot rolling technology in the temperature range of austenite in order to produce ferrite grain sizes and mechanical characteristics which are demanded.

The relationship between the calculated ferrite grain size d_α and the yield strength R_e as well as the tensile strength R_m follows by superposition of the Peierls- Nabarro- stress σ_i , solid solution hardening (pearlite), transformation hardening and grain refinement according to F.B.Pickering /9/:

$$R_e = \sigma_i + A*(\%Mn) + B*(\%Si) + C*fp(\%) + D*d_\alpha^{-1/2} \quad (10)$$

$$R_m = \sigma_0 + E*(\%Mn) + F*(\%Si) + G*fp(\%) + H*d_\alpha^{-1/2} \quad (11)$$

σ_0 , A* to H* - regression coefficients

d_α - mean value of the ferrite grain size

fp - volume content of pearlite.

Quantitative analysis of the microstructure of 41 plates, 10 to 40 mm thickness, from different steel grades (StE355, St38-3, St38b-2, RSt37-2) was applied to prove the above equations. The measurements of the mean ferrite chord length and of the volume content of pearlite was carried out at all 41 plates in the x-z plane (x- rolling direction, z- thickness direction), distributed across the plate thickness both in rolling and in thickness direction. For the determination of the mean value of the ferrite chord length d_α and of the volume content of pearlite fp 4000 to 6000 measuring values for each plate were used in dependence on the plate thickness. The yield strength and the tensile strength can be calculated by means of the measured d_α - and fp- values according to the equations (10) and (11) with an accuracy of ± 20 MPa and ± 15 MPa, respectively. The pearlite algorithm yields the volume content fp with an accuracy of $\pm 2,2\%$ /10/.

PLATE ROLLING

Figure 4 shows ferrite grain size values, calculated by the computer program for the middle of the plate thickness, in relation to measured values. The retardation of the ferrite grain growth after the γ/α - transformation for the steel grade RSt37-2 was not taken into account. Therefore, the calculated d_α - values are somewhat higher than the measured values. The d_α - values for the steel St24 refer to strip which was produced on a thin slab casting and rolling equipment. The chemical composition of the melts given from the steel plant and the rolling schedule dates including temperatures from a process control system of a 4- high plate mill were used to calculate the yield strength values of the as- rolled plates. The calculated values are compared with yield strength dates which were determined by the quality control department of the rolling mill (**Figure 5**) /6/.

HOT STRIP ROLLING

The suitability of the above mentioned algorithms for hot strip rolling is demonstrated by **Figures 6 to 8**. From the quality control department measured yield strength values are compared with values calculated by means of the chemical composition of the selected melts as well as by means of the applied rolling schedules and cooling dates /7/.

UNIVERSAL BEAM ROLLING

The deformation of the web and of the flanges can be considered approximately as a rolling process between flat rolls. By means of a two- dimensional temperature model including rolling schedule dates for web and flanges it is possible to analyse the influence of different cooling technologies on the microstructural homogeneity in the cross section of the as- rolled beams. Variations of the ferrite grain size can be evaluated concerning the demanded yield strength level (**Figure 9**). The designer or operator of a universal beam rolling mill can estimate by computer simulation which quality effect could be have a projected modification of the rolling mill.

CONCLUSIONS

Microstructure models can be applied for the quality assurance at hot rolling and for the further development of hot rolling processes.

The on- line application of such models in process control systems of rolling mills will further improve the quality level of the rolled products.

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Figure 1 Application of microstructural models

Table 1. Algorithms for describing the evolution of the microstructure in unalloyed C-Mn steels during hot rolling

$$X = 1 - \exp(-k \cdot t^n) \quad (1)$$

$$k = k_0 \cdot \exp(-Q_{\text{rec}}/R \cdot T) \quad (2)$$

$$X = 1 - \exp\{-2.996(t_p/t_{0.95})^2\} \quad (3)$$

$$t_{0.95} = A' \cdot Z^{-3/8} \cdot \phi_v^{-4} d_0^2 \cdot \exp(Q_{\text{rec}}/R \cdot T) \quad (4)$$

$$Z = \dot{\phi}_v \cdot \exp(Q_{\text{def}}/R \cdot T) \quad (5)$$

$$d_{\text{rec}} = A'' \cdot (\beta - 1 \ln Z/A)^{-2/3} \cdot \phi_v^{-1} \cdot d_0^{1/2} \quad (6)$$

$$d_\gamma = (d_{\text{rec}}^{10} + A''' \cdot t \cdot \exp\{-Q_{\text{gg}}/R \cdot T\})^{0.1} \quad (7)$$

$$d_{\alpha 0} = a + b \cdot \dot{T}^{-1/2} + c(1 - \exp\{-0.015 \cdot d_\gamma\}) \quad (8)$$

$$d_\alpha = d_{\alpha 0}(1 - 0.45 \cdot \phi_{v,\text{eff}}^{1/2}) \quad (9)$$

Table 2. List of symbols

A, A', A'', A'''	constants
β , k_0 , a, b, c, n	
d_0	initial austenite grain size
d_{rec}	recrystallized austenite grain size
d_γ	austenite grain size
Q_{rec}	activation energy for static recrystallization
Q_{gg}	activation energy for grain growth
Q_{def}	activation energy for hot deformation
X	statically recrystallized fraction of austenite
R	gas constant
t	time
$t_{0.95}$	time for complete static recrystallization
T	temperature
$\dot{T}$	cooling rate
Z	Zener Hollomon parameter
ϕ_v	equivalent logarithmic strain
$\dot{\phi}_v$	equivalent logarithmic strain rate
$\phi_{v,\text{eff}}$	effective logarithmic strain
$d_{\alpha 0}$	ferrite grain size after complete static recrystallization of austenite
d_α	ferrite grain size after uncomplete static recrystallization of austenite

Figure 3 Layout of the applied microstructure computer program

Figure 4 Comparison between calculated and measured ferrite grain size values for plates, thickness 8 to 50 mm, as well as for hot rolled strip St24, thickness 3mm, produced in a thin slab casting and rolling process

Figure 5 Calculated yield strength values in relation to measured values for 8 to 50 mm thick plates

Figure 6 Comparison between measured and calculated ferrite grain size values for hot rolled strips, surface and thickness centre

Figure 7 Measured yield strength values in relation to calculated values for hot rolled strips, thickness 2,2 to 3,8 mm, all measured values parallel to rolling direction

Figure 8 Comparison between measured and calculated tensile strength values for hot rolled strips, thickness 2,2 to 3,8 mm, all measured values parallel to rolling direction

Figure 9 Simulation results for hot rolling of universal beams 914 mm x 419 mm, St52, by application of different cooling technologies, Re - yield strength, dα - ferrite grain size