Mill Process Calculations – A Design and Optimization Tool for Wire Rod and Bar Mills developed at the University of Duisburg-Essen

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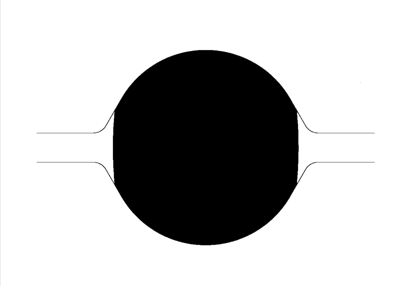
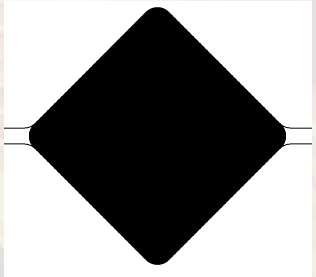
Scope

- Introduction to Roll Pass Design and Groove Sequences
- The Mill Process Calculations (MPC) Geometry system
- Submodels of MPC
  - Roll Force and Torque
  - Spreading Calculation and Rectangular Equivalence Method
  - Material Models: Flow Stress and Spreading Behaviour
  - Calculation of Mill Temperature Profiles
  - Elastic Stand Feedback and Interstand Tensions
- Example Calculations

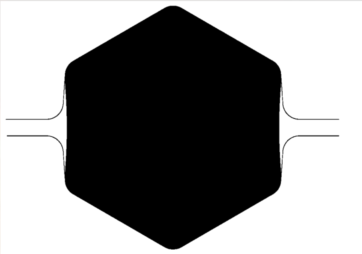
Section Shapes to be calculated using MPC



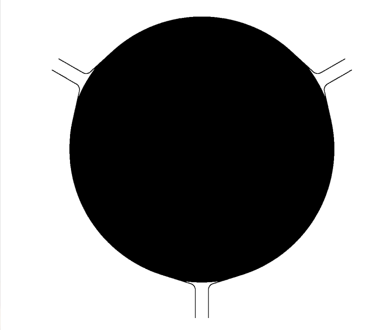
Rounds



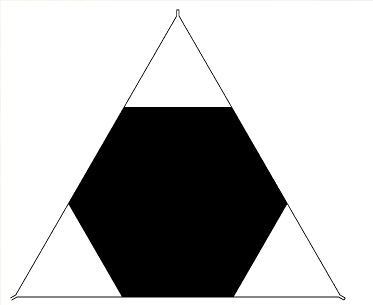
Squares



Hexagons



Rounds (3-Roll)

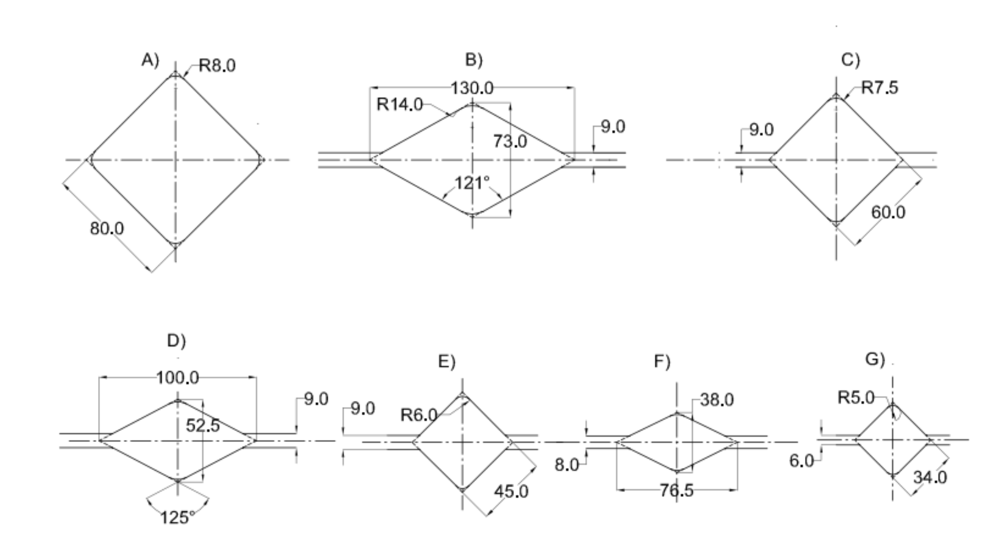


Hexagons (3-Roll)

„Until few decades ago, roll pass design was a kind of secret art, inherited from one to the next pass designer of a rolling mill, carried out behind closed doors of their office rooms, just like the art of gold making in the laboratories of the alchemists.“

Wilhelm Tafel, „Rolling and Roll Pass Design“ (1923)

Design of Groove Sequences



$$\lambda_{tot} = \frac{A_0}{A_e}$$ (total elongation)

$$\lambda_{tot} = \lambda_{mean,seq}{}^{N}$$ (total elongation expressed by the sequence elongation and the number of sequences N)

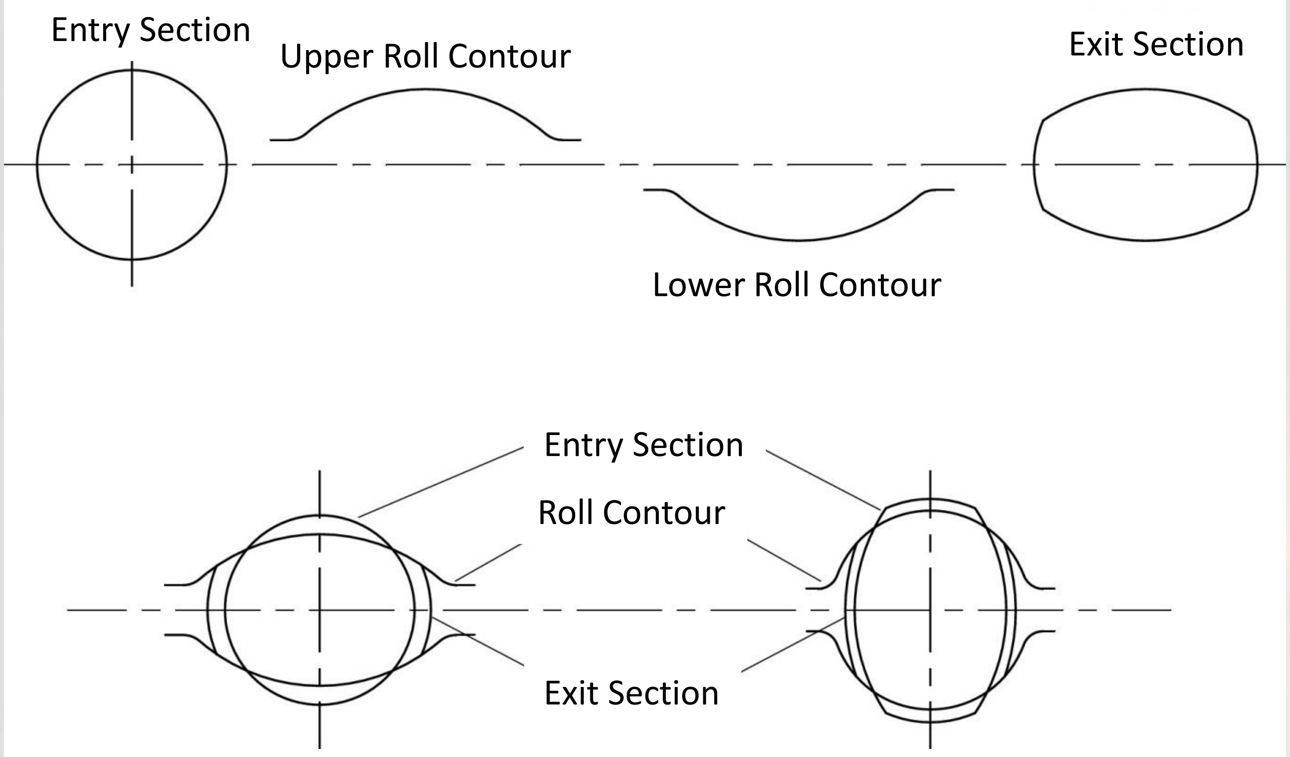
$$N = TRUNC\left(\frac{\ln \lambda_{tot}}{\ln \lambda_{mean,seq}}\right) + 1$$

(number of sequences needed for a given elongation)

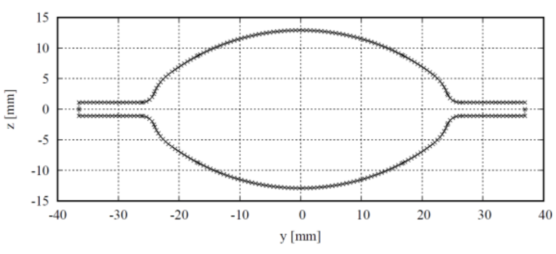
$$\lambda_{seq,i} = \lambda_{mean,seq} \cdot Z^{y_i}$$ (degressive elongation distribution for Z > 1)

Example: 80 mm square to 34 mm square in 6 passes (3 sequences)
square – diamond – square pass sequence

MPC Geometry System; Polygonal Contours



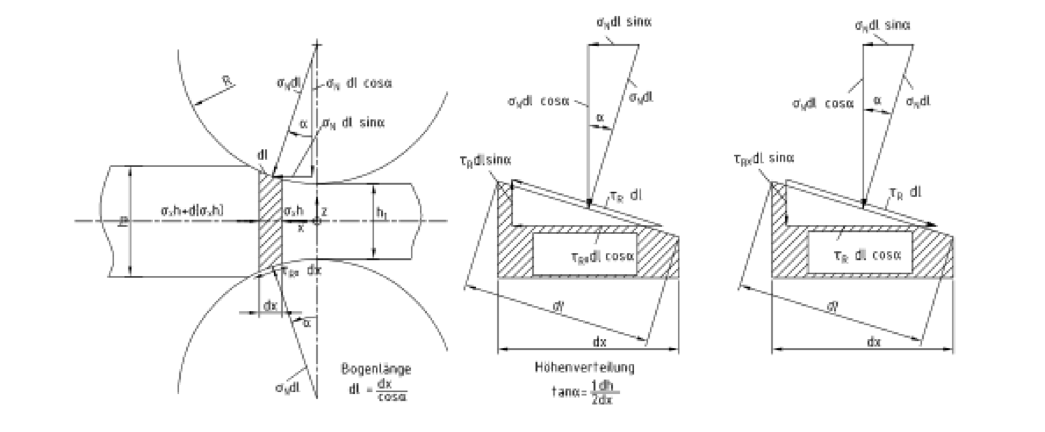
Computer simulation of the rolling process with aid of numeric contours



Methods of pass design assessment and optimization in MPC:

- Simulation of groove sequences with given geometries
- Optimization of screw-down for given groove filling ratios
- Optimization with iterative refinement of grooves, also complete redesign is possible

Calculation of Roll Force and Torque



Slab theory acc. to von Karman, leading to differential equation of the roll gap:

$$\frac{d\left(\sigma_x h\right)}{dx} = \sigma_N \frac{dh}{dx} \pm 2\tau_F$$

For pure sticking friction, $\tau_F = \frac{k_f}{\sqrt{3}}$ and constant flow stress, we arrive at equations for roll force and torque:

$$F_W = b_m k_{fm} \sqrt{r \Delta h} \bullet Q_P$$

$$M_{dges} = 2 \cdot b_m k_{fm} r \Delta h \bullet Q_M$$

With: $$Q_P = \frac{\sigma_R}{k_{fm}} + 2\sqrt{\frac{1-\varepsilon_h}{\varepsilon_h}} \arctan\left(\sqrt{\frac{\varepsilon_h}{1-\varepsilon_h}}\right) - 1 + \sqrt{\frac{r}{h_1}}\sqrt{\frac{1-\varepsilon_h}{\varepsilon_h}} \ln \frac{\sqrt{1-\varepsilon_h}}{1-\varepsilon_h (1-\beta_F{}^2)}$$

$$Q_M = \sqrt{\frac{r}{h_1}}\sqrt{\frac{1-\varepsilon_h}{\varepsilon_h}}\left(\frac{1}{2} - \beta_F\right)$$

$$\beta_F = \left(\frac{\alpha_F}{\alpha_0}\right) = \sqrt{\frac{1-|\varepsilon_h|}{|\varepsilon_h|}} \tan\left\{\frac{1}{2}\sqrt{\frac{h_1}{r}}\left[\frac{\sigma_R - \sigma_V}{k_{fm}} + \ln\left(1-|\varepsilon_h|\right)\right] + \frac{1}{2}\arctan\sqrt{\frac{|\varepsilon_h|}{1-|\varepsilon_h|}}\right\}$$

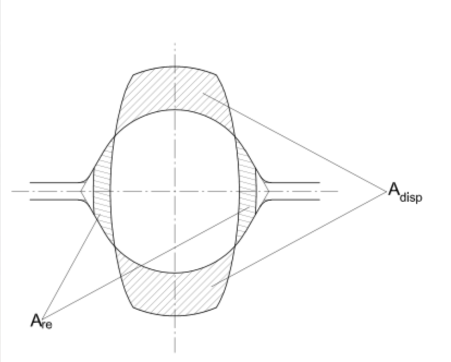
Spread Calculation

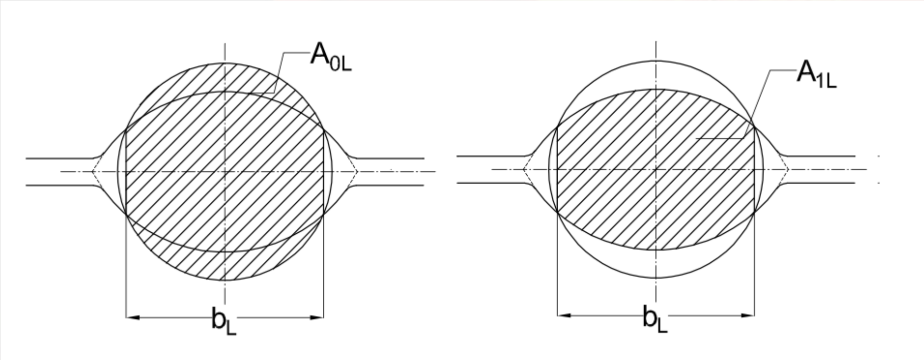
Marini's spread equation:

$$b_1 = b_0 + \frac{2B\cdot\Delta h\cdot b_0\cdot\left(\frac{d_w - h_0}{2}\right)}{0,91\cdot\frac{b_0+3h_0}{4h_0}\cdot\left(hb_0 + b_0\frac{h_0+h_1}{2}\cdot\frac{1+A}{1-A}\right)+h\cdot d_w\cdot B}$$

$$A = \frac{\sqrt{\Delta h}}{2\mu\sqrt{\frac{d_w}{2}}}$$

$$B = \sqrt{\frac{2\Delta h}{d_w}}$$





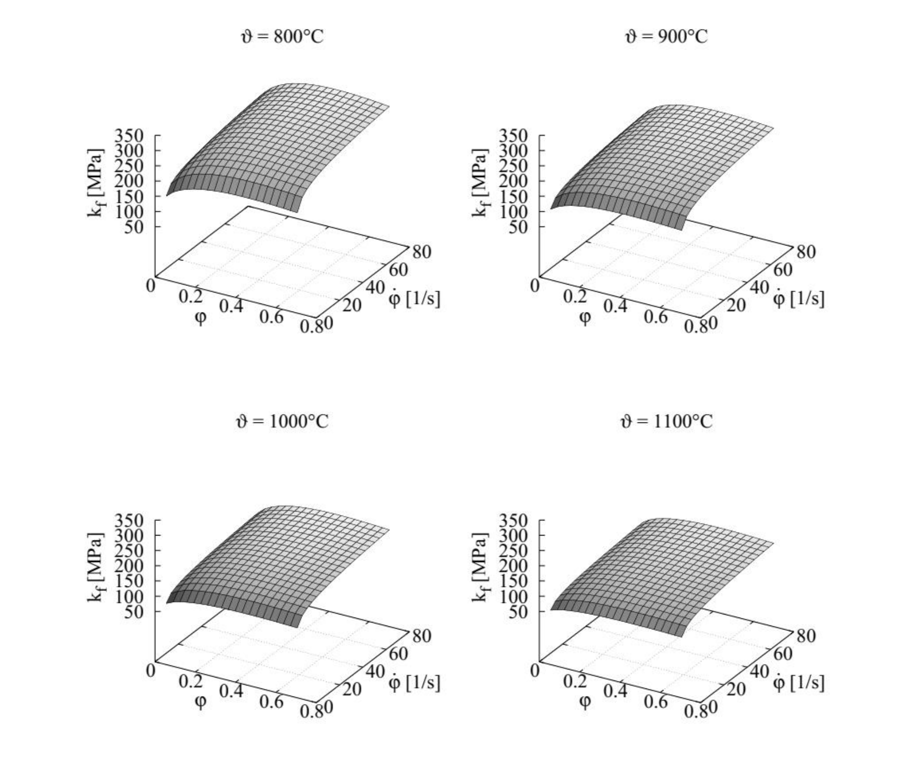
$$h_{1L} = \frac{A_{1L}}{b_L} = \frac{b_L h_1 - 2b_L R + b_L\sqrt{R^2 - \frac{b_L^{\,2}}{4}} + 2R^2\arcsin\left(\frac{b_L}{2R}\right)}{b_L}$$

$$b_L = 2\sqrt{R - \left(\frac{h_1 R - \frac{h_1^{\,2}}{4} - R^2}{h_1 - 2R}\right)^2}$$

(analytical solution for the pass Round in Oval)

Equivalence Method, based upon works by A.E. Lendl and P.J. Mauk

Material Modeling 1 – Flow Curves



Flow stress of the carbon steel C55 as a function of temperature, strain rate and strain

$$k_f\left(\varphi,\dot{\varphi},\vartheta\right)=Ke^{m_1\vartheta}\dot{\varphi}^{m_2+m_5\vartheta}\varphi^{m_3}e^{m_4\varphi}$$

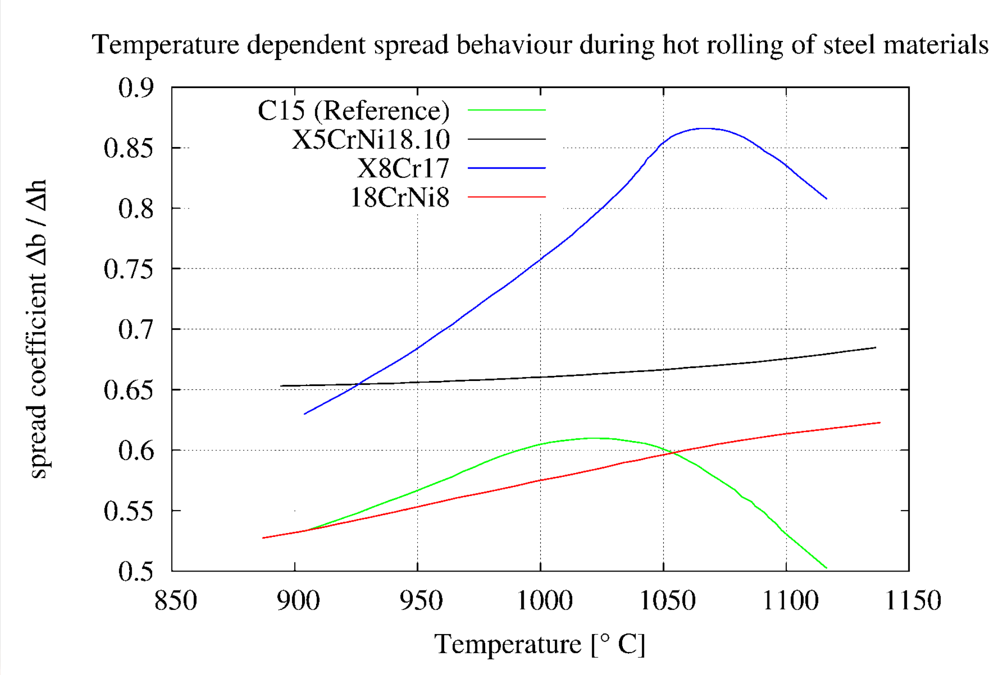
The „Duisburg Approach“ for hot flow curves (Function No. 8 acc. to Gottschling and Mauk)

Coefficients of this function are available for a set of 270 steel materials

$$k_{fm}=\int_{\varphi_0}^{\varphi_1}\int_{\dot{\varphi}_0}^{\dot{\varphi}_1}\int_{\vartheta_0}^{\vartheta_1}k_f\left(\varphi,\dot{\varphi},\vartheta\right)d\vartheta\, d\dot{\varphi}\, d\varphi$$

(mean flow stress for simplified rolling models)

Material Modeling 2 – Spread behaviour



After experiments carried out by Grosse and Gottwald (1951)

$$f_b = \frac{\left(\frac{\Delta b}{\Delta h}\right)}{\left(\frac{\Delta b}{\Delta h}\right)_{ref}}$$

The temperature-dependent spread factors are available for a set of common steel materials

A newer approach is the prediction of the material dependent spreading by the use of artificial neural networks (see presentation by Maik Tino Gruszka in session *Mathematical Modeling and Simulation VI* on Friday)

Temperature Field Calculations

One-dimensional axisymmetric heat equation:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda \frac{\partial T}{\partial r}\right) + s_q$$

Mathematical Formulation

$$aT_{i,k} + bT_{i-1,k} + cT_{i+1,k} = T_{i,k-1} + \frac{\Delta t\, s_{q,i,k-1}}{\rho_{i,k-1} \cdot c_{p,i,k-1}}$$

Finite Difference Approximation

Numerical solution by finite differences (one linear system for one time k), boundary conditions are given by the mill layout in a layout data file. (excerpt example given below)

```
; --- Roughing Mill
G 01H  K  680.    850.   MOTOR1          43.4279     0.975   210.    0.3
L 6
G 02V  K  680.    850.   MOTOR1          33.7079     0.975   210.    0.3
L 6
G 03H  K  650.    700.   MOTOR1          25.9426     0.975   210.    0.3
L 4
G 04V  K  650.    700.   MOTOR1          19.5059     0.975   210.    0.3
L 4
G 05H  K  520.    650.   MOTOR1          22.8798     0.975   210.    0.3
L 5
G 06V  K  520.    650.   MOTOR2          9.0514      0.975   210.    0.3

; -- To Intermediate Mill …
L 75.
```

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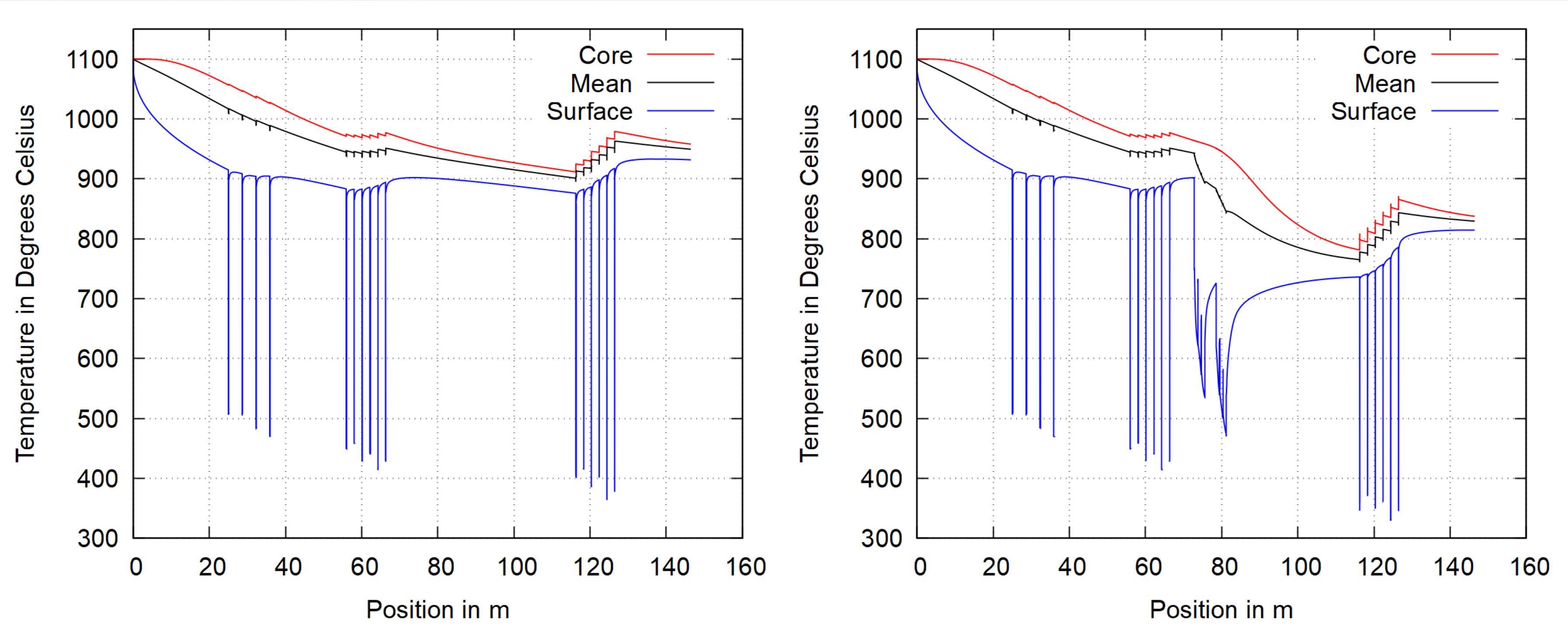
Example for a temperature field calculation in a bar mill



Data of this example available online !

https://www.uni-due.de/umf/mpc.php

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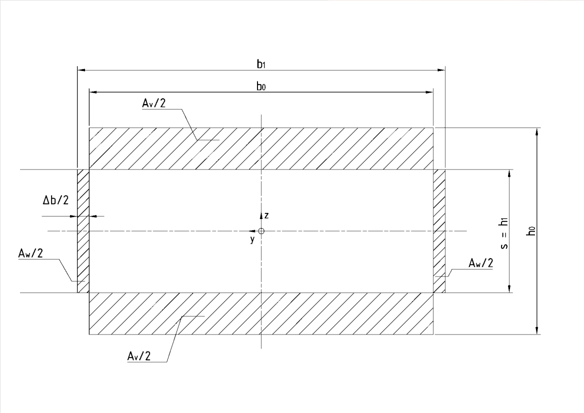
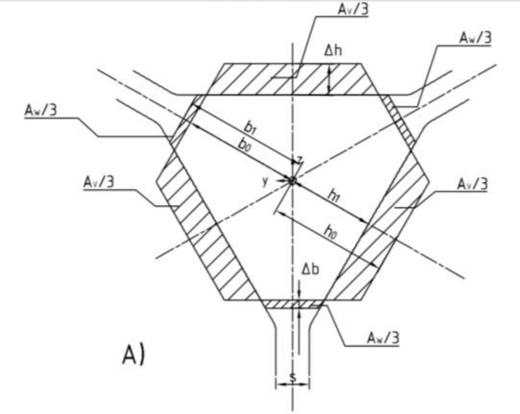
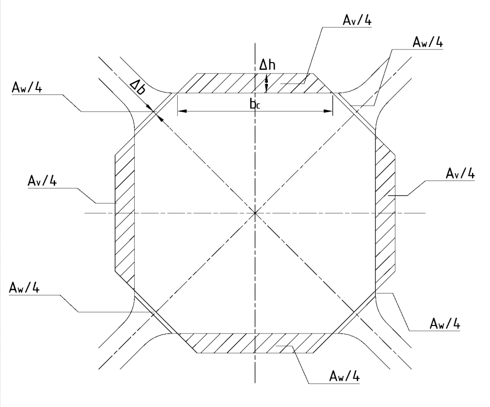
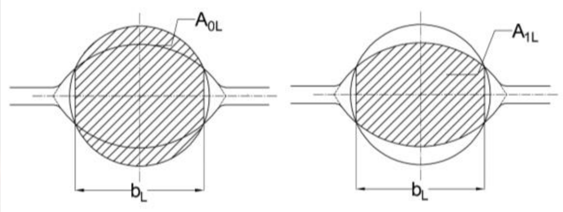
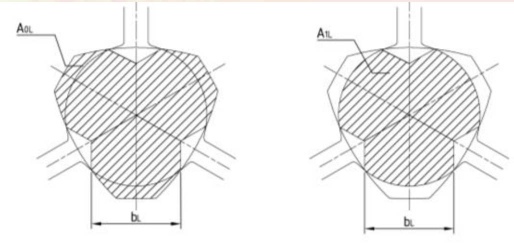
Three-Roll and Four-Roll Rolling Techniques (1)

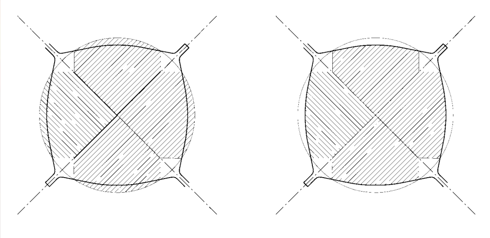




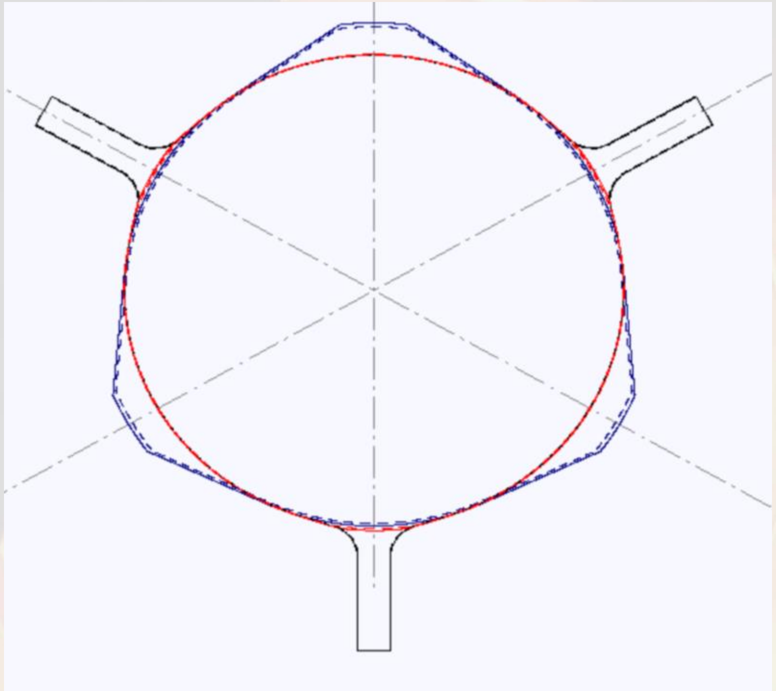


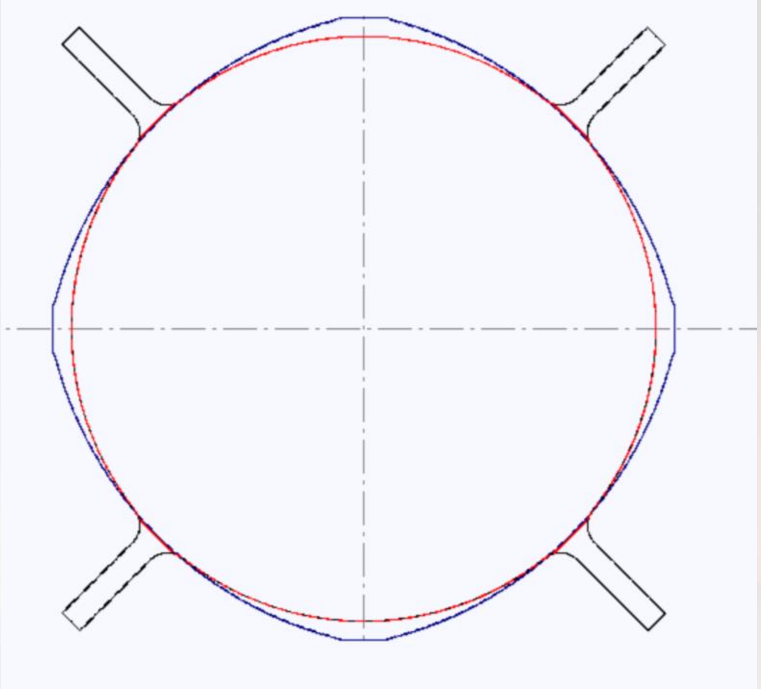






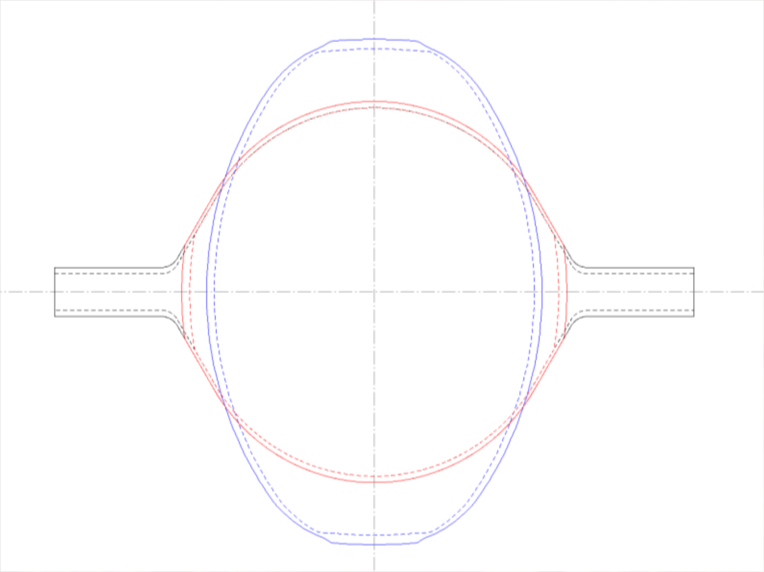
Three-Roll and Four-Roll Techniques (2)



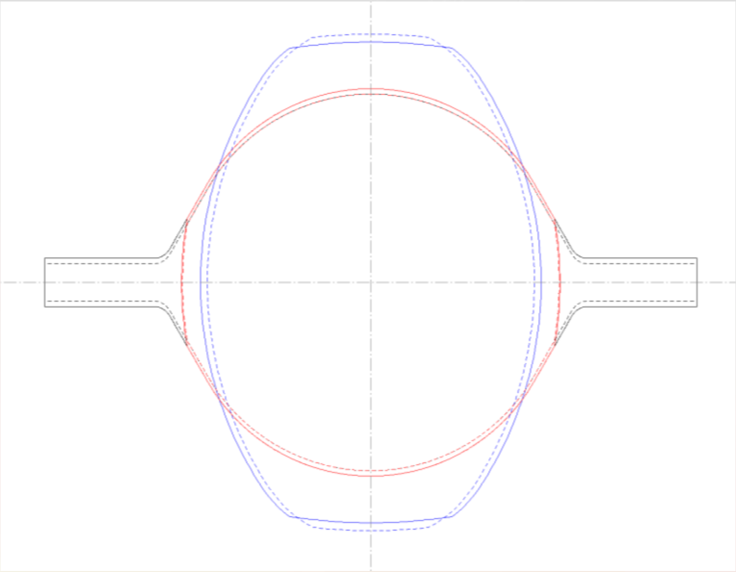


Ch. Overhagen: Pass Design Methods for Three- and Four-Roll Rolling Processes – Comparison and Analysis, 11th International Rolling Conference, Sao Paulo, Brazil, 2019

Example Calculations – Elastic Stand Feedback



A) Effects of Elastic Feedback



B) Effects of Elastic Feedback combined with Interstand Tensions

Data of this example available online !

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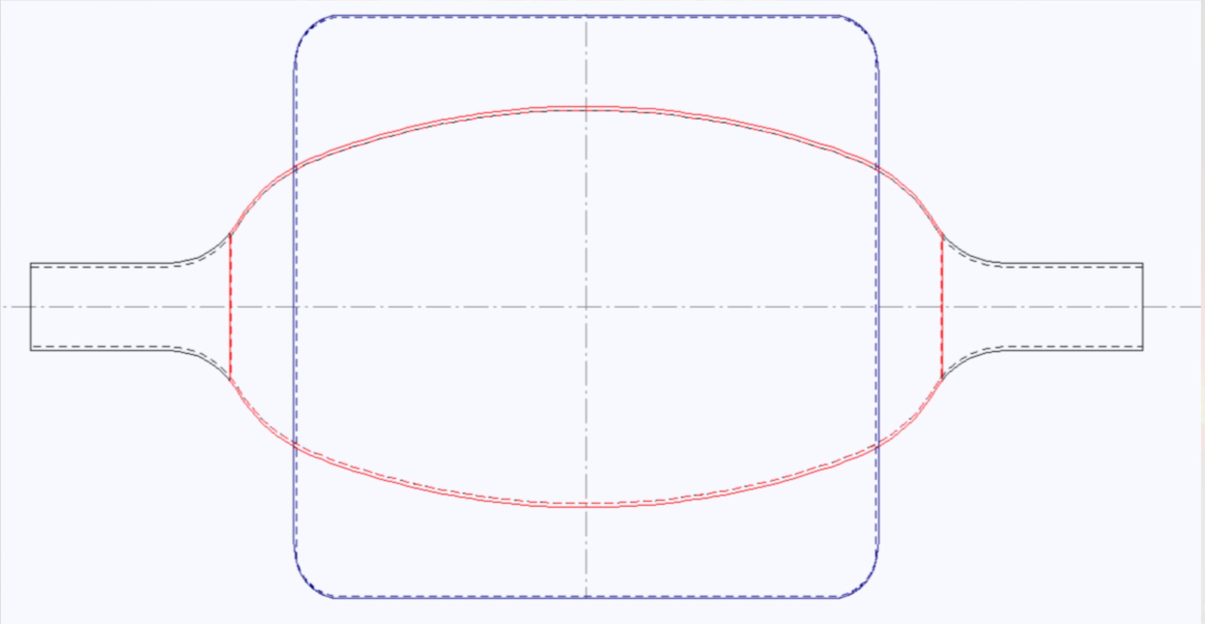
Elastic feedback of the rolling stands

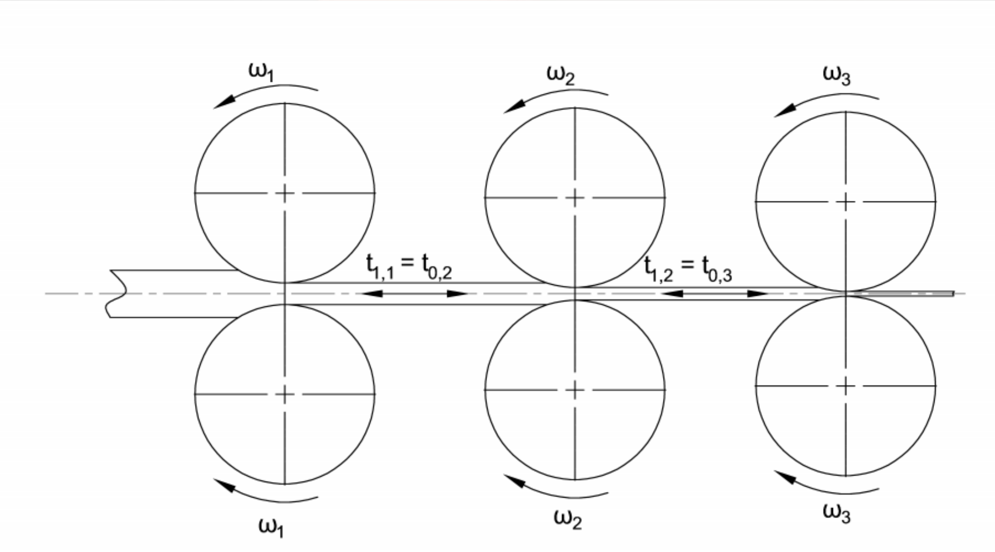
Gagemeter Equation: $$s' = s_o + \frac{F}{C_S}$$



s' : Roll gap under load [mm]
s_0 : Unloaded roll gap [mm]
F : Rolling Force [kN]
C_S : Elastic Modulus of Rolling Stand [kN/mm]

Dashed lines: rigid stands
Solid lines: with elasticity

Interstand Tension Assessments



$$\omega_i = f\left(t_0, t_1, \dot{V}\right)$$

$$\omega_i = \omega_{0,i} + a_i t_{0,i} + b_i t_{1,i}$$

Change of the roll speed due to change of the tensions:

$$\Delta\omega_i = a_i \Delta t_{0,i} + b_i \Delta t_{1,i}$$

Change of the roll speed difference of two successive stands due to change of the tensions:

$$\Delta\omega_{i+1} - \Delta\omega_i = \left(a_{i+1} - b_i\right)\Delta t_{1,i} - a_i \Delta t_{0,i} + b_{i+1}\Delta t_{1,i+1}$$

$$\varphi_l = \varphi_{l0} + \Delta\varphi_{l\sigma}$$

$$\Delta\varphi_{l\sigma} = k_1\left(\frac{t_0}{k_{fm}}\right)^2 + k_2\left(\frac{t_0}{k_{fm}}\right) + k_3\left(\frac{t_1}{k_{fm}}\right)$$

$$k_i = m_{1i}\frac{\Delta h}{h_0} + m_{2i}\frac{b_0}{h_0} + m_{3i}\frac{A_d}{A_m}\ ;\ i = 1 \ldots 3$$

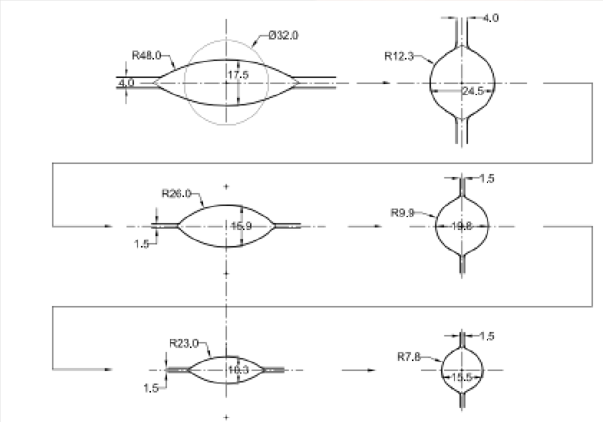
$$a_i = \frac{\partial\omega_i}{\partial t_{0,i}} = \frac{\partial\omega_i}{\partial\alpha_{N,i}} \cdot \frac{\partial\alpha_{N,i}}{\partial t_{0,i}}$$

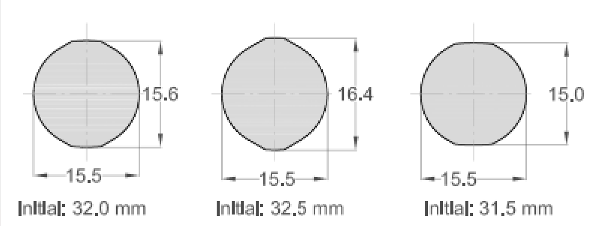
$$b_i = \frac{\partial\omega_i}{\partial t_{1,i}} = \frac{\partial\omega_i}{\partial\alpha_{N,i}} \cdot \frac{\partial\alpha_{N,i}}{\partial t_{1,i}}$$

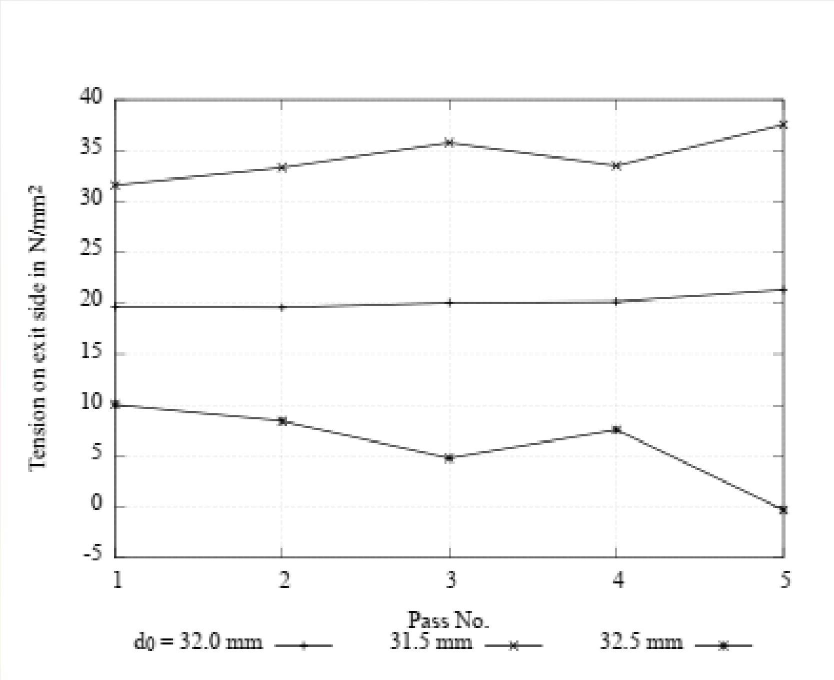
Leads to a linear equation system for the unknown tensions

$$\mathbf{At} = \mathbf{w}$$

Example Calculations – Assessment of interstand tensions







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Summary

- Grown in 15 years of continuous development, MPC today is a software package that can aid the pass designer or rolling mill engineer in new- or redesigning groove sequence, or in optimization of the rolling processes.
- The assessment of interstand tensions can be carried out with MPC from known groove setups and roll speeds. The knowledge of the acting tensions is an important building block towards the digital twin of a section rolling process.
- The three- and four-roll technologies are implemented, enabling MPC to be used for optimization of these rolling processes

Thank you for your interest !

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MPC is available to industrial partners as part of a training programme in rolling theory and roll pass design. **Please contact me if you are interested !**

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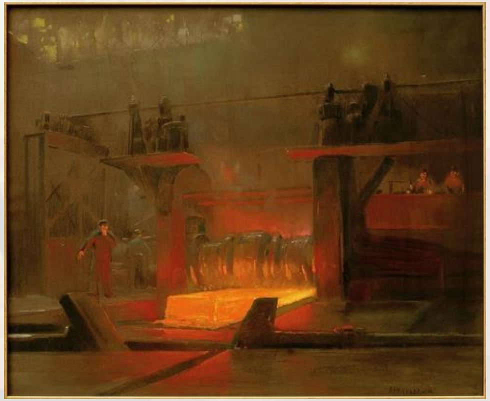
Pieter Josseling de Jong:
„Wire Rod Mill, England“ (1885)

Adolph von Menzel: „The Iron Rolling Mill“ (1875)



Herman Heijenbrock: „Workers in the Rolling Mill“ (1915)

Arthur Kampf: „Rolling Mill“ (1904)

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