# *C - Process Models*

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# 1. RIGHT OF USE

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# 2. General

Aim of this specification is the definition of the functions which cover the calculation of set points within the HSM level 2 system for the ARMCO HSM installation in Mansfield. All these functions together are called *Process Models*.

Covered Areas:

- Finishing Mill

The set-point-calculation for the finishing mill area consists of a number of predictive model components, having a well defined interface and each covering a certain area of the set-point-calculation. These predictive models consist of the items as mentioned below:

- Rolling strategy
- Roll force and torque model
- Material equation
- Roll gap temperature model
- Radiation temperature model
- Descaling and cooling Model
- Heat cover temperature model
- Temperature and speed calculation
- Width model
- Gauge meter model
- Roll wear model
- Roll deflection model
- Thermal work roll model

- Mass flow considerations
- Calculation of transfer bar thickness

In order to improve the accuracy of the prediction of the above mentioned models the models have learning capability by the aid of adaptive parameters where it is appropriate and applicable. These parameters will be adapted during rolling based on actual process measurements. The learning feature includes the below mentioned adaptation mechanism:

- Temperature adaptation
- Thickness adaptation
- Adaptation of material equation
- Strip segment tracking
- Adaptation of stand speed
- Adaptation of transferbar delivery time
- Fit of mill stretch curve

The strip segment tracking function delivers the required tracking information to the other adaptation functions.

Some basic parameters which are required for a complete mill-set-up and which reflect some technological and/or operational requirements are stored in the below mentioned look-up tables:

- Rolling strategy table
- Looper table
- Descaler table
- Interstand cooling table

# 3. Functions

For the computation of the relevant set-points for the control of the rolling process, combinations of the mentioned process models are used. Furthermore such a computation process is called a function. The set-point-calculation comprehends the functions as mentioned below :

**Precalculation of finishing mill pass schedule**

The precalculation of the pass schedule for the finishing mill is triggered when the slab is charged in the reheat furnace, when the slab is discharged and on operator request.

**Calculation of finishing mill pass schedule**

The calculation of the pass schedule for the finishing mill is triggered when the actual values of the last load pass in the roughing mill are available.

**Operator requested precalculation of the finishing mill pass schedule**

The operator can request a pass schedule precalculation for any slab that is in the furnace or in the roughing mill area until the time of F2 threading.

**Adaptation of model parameters**

The actual gathered measured values will be used to improve the foreseen adaptation parameters of the process models. These is done just after the strip is finished.

The improved model parameters come into effect either for the next strip of the same class (strip related parameter) or for the next strip regardless of the class (plant related parameter).

**Off-line- Adaptations**

The below mentioned adaptation functions are no standard adaptation functions. They will be executed when no rolling is going on or during test rolling:

- Adaptation of thermal work roll crown
- Adaptation of work roll wear
- Fit of mill stretch curve

# 4. Prediction Models

## 4.1 Rolling Strategy

### Description

The rolling strategy is the basis for the distribution of thickness reductions over all stands. Two rolling strategies are provided: "Force" strategy is based on a target rollforce for the last stand and a rollforce slope for the upstream stands to meet an optimum strip flatness, while "Load"-strategy bases on a set of stand specific relative thickness reductions to meet an optimum motor load distribution. "Load"-strategy allows the operator to modify the absolute thickness reduction each stand to adjust the pass schedule to the profile and flatness requirements.

For both strategies, the calculation is an iterative process, which makes frank use of the various sub models like 'force and torque model', 'temperature models' etc. The basic principle of the calculation is to make the pass schedule consistent with the below mentioned boundaries:

- Roll force distribution
- Max. rolling force
- Max. rolling torque considering overload
- Max. relative thickness reduction
- Max. bite angle
- Target finishing temperature
- Constant mass flow within finishing mill

### Input values

Strip data

| | |
|---|---|
| $i_{sgcl}$ | Steel grade class index [1] |
| $h_{trb}$ | Transfer bar thickness [in. -> mm] |

| | |
|---|---|
| $w_{trb}$ | Transfer bar width [in. -> mm] |
| $T_{entry}$ | Entry temperature F1 [°F -> °C] |
| $h_{strip}$ | Target strip thickness [in. -> mm] |
| $T_{exit}$ | target finishing temperature [°F -> °C] |

Stand data

| | |
|---|---|
| $F_{max}(i_{stno})$ | Max. roll force [lb -> kN] |
| $TOR_{\max}(i_{stno})$ | Max. roll torque [lb·ft -> kNm] |
| $ovl(i_{stno}, t)$ | Max. percentage overload [%] |
| $E(i_{stno})$ | YOUNG's modulus work roll [psi -> N/mm²] |
| $\nu(i_{stno})$ | POISSON's ratio work roll [1] |
| $v_{w,\max}(i_{stno})$ | Max. rolling speed [rpm] |
| $v_{nom}(i_{stno})$ | Nominal speed [rpm] |
| $r_{up}(i_{stno})$ | Upper work roll radius [in. -> mm] |
| $r_{lo}(i_{stno})$ | Lower work roll radius [in. -> mm] |
| $tens_f(i_{stno})$ | Forward tension stress (specific tension) [psi -> N/mm²] |
| $tens_b(i_{stno})$ | Backward tension stress (specific tension) [psi -> N/mm²] |

Strategy data

| | |
|---|---|
| $F_{spec,F6}$ | Specific target roll force F6 [lb/in. -> kN/mm] |
| $grad_{F_{spec}} = \frac{dF_{spec}}{dh_{exit}}$ | Slope of spec. roll force distribution [psi -> kN/mm²] |

| | |
|---|---|
| $F_{spec,\max}$ | Specific max. roll force [lb/in. -> kN/mm] |
| $eps_{\max,i_{stno}}$ | Max. percentage reduction [%] |
| $eps_{set,i_{stno}}$ | Preset percentage reduction [%] |
| $epsoper_{i_{stno}}$ | Operator corrected percentage reduction [%] |
| $abscor_{i_{stno}}$ | Operator correction in absolute reduction [in/1000] |
| $v_{w,\max}$ | Max. rolling speed F6 [ft/min -> m/s] |
| $\alpha_{\max}$ | Max. bite angle [rad] |
| $ovl_{\max}$ | Max. percentage overload [%] |

### Output values

| | |
|---|---|
| $h(i_{stno})$ | exit thickness [mm -> in.] |
| $F(i_{stno})$ | Roll force [kN -> lb] |
| $TOR(i_{stno})$ | Roll torque [kNm -> lb·ft] |
| $v_w(i_{stno})$ | Rolling speed [m/s -> ft/min] |

### Submodels

Roll force and torque model
Roll gap temperature model
Radiation temperature model
Descaling and cooling model
Mass flow considerations
Temperature and speed calculation

### Model equations for "Force" strategy

The task of the rolling strategy is to compute the exit thicknesses such that the following restrictions are fulfilled and targets are met:

(R1) Target roll force (Max. roll force & Shape control)

(R2) Maximum reduction

(R3) Maximum bite angle

(R4) Maximum roll torque

(R5) Finishing thickness

(R6) Finishing temperature

The computation starts with the transfer bar thickness (say $h_1$), the entry temperature at F1 (say $T_1$) and an initial rolling speed (say $v_1$), that is iterated later on in order to achieve the finishing temperature (R6). By (R2),(R3) and (R5) a permissible interval for the first exit thickness (say $h_2$) can be determined:

$$h_{2,\min} < h_2 < h_{2,\max}$$

(R1) can be considered as a function of the exit thickness:

$$h_{ex} \ \alpha \ F_{tar}(h_{ex})$$

The exit thickness will be computed as solution of the equation:

$$F_{tar}(h_{ex}) - F_{\mathrm{mod}}(h_{ex}) = 0, \quad h_{ex} \in [h_{2,\min}, h_{2,\max}]$$

where $F_{\mathrm{mod}}$ is the roll force computed by the roll force model

Because of the monotonicity

$$h_{ex} < h'_{ex} \Rightarrow F_{\mathrm{mod}}(h_{ex}) > F_{\mathrm{mod}}(h'_{ex})$$

the following three cases are possible only for above equation:

$$\text{Case 1: } F_{\mathrm{mod}}(h_{2,\min}) > F_{tar}(h_{2,\min}) \wedge F_{\mathrm{mod}}(h_{2,\max}) < F_{tar}(h_{2,\max})$$

$$\text{Case 2: } F_{\mathrm{mod}}(h_{2,\min}) < F_{tar}(h_{2,\min}) \wedge F_{\mathrm{mod}}(h_{2,\max}) < F_{tar}(h_{2,\max})$$

$$\text{Case 3: } F_{\mathrm{mod}}(h_{2,\min}) > F_{tar}(h_{2,\min}) \wedge F_{\mathrm{mod}}(h_{2,\max}) > F_{tar}(h_{2,\max})$$

If case 1 occurs the equation can be solved by a rapid secant method. Case 2 means, that for any exit thickness in the permissible interval the predicted roll force remains below the restriction. Therefore we can put

$$h_2 := h_{2,\min}$$

If case 3 occurs there will be no permissible solution of the problem. This case is only theoretical and usually does not occur in practice. The next step is to check the torque restriction (R4) for the calculated exit thickness. If it is not fulfilled, the exit thickness will be increased till the torque restriction is met. Now the exit speed will be determined and hereby the entry temperature for the next pass. The described procedure will be repeated to get the next exit thickness. The rolling speed is determined such that the entry speed coincides with the exit speed of the previous pass. This process will be continued till the final thickness is met. If the necessary number of passes exceeds 6 the target roll force distribution (R1) is slightly modified and the whole computation is repeated. If it turns out that it will not be possible to roll the final gauge without exceeding the mill limits, the final gauge will be incremented and a warning is given to the operator. Because of the inequality

$$h_2 \geq h_{strip} := \text{target strip thickness}$$

in general the following inequality holds for the last pass:

$$F_{\mathrm{mod}}\left(h_{strip}\right) \leq F_{tar}\left(h_{strip}\right) = F_{F6} \cdot w_{trb}$$

If the relative error exceeds a certain tolerance the restriction (R1) is modified till the above inequality comes close to an equality.

**Internal values**

none

**Calculation sequence**

The calculation makes frequent use of the models mentioned above and is highly iterative. The calculation sequence coincides with the procedure described above.

**Model equations for "Load" strategy**

The task of the rolling strategy is to compute the exit thicknesses such that the following restrictions are fulfilled and targets are met:

(R1) Preset relative reductions each stand

(R2) Absolute draft correction by the operator

(R3) Finishing thickness

(R3) Finishing temperature

(R4) Maximum reduction

(R5) Maximum bite angle

(R6) Maximum roll torque

The computation starts with the transfer bar thickness ($h_{Trb}$), the entry temperature at F1 ($T_1$) and an initial rolling speed ($v_1$), which is iterated later on in order to achieve the finishing temperature (R4).

The given relative reductions result in an exit thickness:

$$h_{Strip} = h_{Trb} \bullet \prod_{i_{stno} = firstS\tan d}^{lastS\tan d} (1 - epsoper_{,i_{stno}})$$

To achieve the exact target strip thickness

$$h_{Strip,\min} < h_{Strip} < h_{Strip,\max}$$

the relative drafts are modified using a parabolic secant methode. Operator corrections are considered

The first exit thickness ($h_{Strip}$) is a result of the preset relative reductions ($eps_{oper,i_{stno}}$ or $eps_{set,i_{stno}}$ if this dimension is rolled for the first time) and the absolute draft corrections done by the operator ($abscor_{oper,i_{stno}}$).

(R1) can be considered as a function of the exit thickness

$$h_{ex} \; \alpha \; eps'_{stno}(h_{ex})$$

where the relative reductions $eps'_{stno}$ are fitted in an iterative process to exactly meet the target thickness.

### Internal values

none

### Calculation sequence

The calculation makes frequent use of the models mentioned above and is highly iterative. The calculation sequence coincides with the procedure described above.

## 4.2 Roll Force and Torque Model

### Description

The 'force and torque model' is used to calculate the roll specific values such as roll force and roll torque, depending on the pass data, like entry and exit thickness for one single pass. The calculation is based on the rolling theory of SIMS. The calculation of the roll force and the roll torque is done straightforward. To make roll force and deformed work roll radius compatible an iteration is performed using the formula of HITCHCOCK.

### Input values

Strip data

| | |
|---|---|
| $h_{trb}$ | Transfer bar thickness [in. -> mm] |
| $h_1$ | Entry thickness [in. -> mm] |
| $h_2$ | Exit thickness [in. -> mm] |
| $w$ | Width [in. -> mm] |
| $T$ | Entry temperature [°F -> °C] |

Work roll data

| | |
|---|---|
| $r_{up}$ | Upper work roll radius [in. -> mm] |
| $r_{lo}$ | Lower work roll radius [in. -> mm] |
| $v_w$ | Rolling speed [ft/min -> m/s] |
| $E$ | YOUNG's modulus [psi -> N/mm²] |
| $\nu$ | POISSON's ratio [1] |

Backup roll data

| | |
|---|---|
| $r_{bu}$ | Backup roll radius [in. -> mm] |
| $r_{bea}$ | Bearing radius [in. -> mm] |
| $\mu$ | Friction coefficent backup roll - bearing [1] |

General data

| | |
|---|---|
| $tens_f$ | Forward tension stress (specific tension) [psi -> N/mm²] |
| $tens_b$ | Backward tension stress (specific tension) [psi -> N/mm²] |
| $i_{sgcl}$ | Steel grade class index [1] |
| $i_{stno}$ | Stand number [1] |

**Output values**

| | |
|---|---|
| $F$ | Roll force [kN -> lb] |
| $TOR$ | Roll torque [kNm -> lb·ft] |
| $h_n$ | Neutral thickness [mm -> in.] |
| $\alpha$ | Roll (bite) angle [rad] |
| $l_d$ | Roll contact length [mm -> in.] |
| $slip_f$ | Forward slip [%] |
| $slip_b$ | Backward slip [%] |
| $v_{entry}$ | Entry speed [m/s -> ft/min] |
| $v_{exit}$ | Exit speed [m/s -> ft/min] |

**Submodels**

Material equation

**Model equations:**

Unique work roll radius [mm]:

$$r = \frac{2 \cdot r_{up} \cdot r_{lo}}{r_{up} + r_{lo}} \qquad \text{Eq. 1}$$

Absolute reduction (draft) [mm]:

$$\Delta h = h_1 - h_2$$ Eq. 2

Relative reduction [1  resp. %]:

$$\varepsilon = \frac{\Delta h}{h_1}$$
$$\varepsilon_{perc} = \varepsilon \cdot 100$$ Eq. 3

Roll contact length [mm]

$$l_d = \sqrt{r' \cdot \Delta h}$$
where $r'$ is the radius of the flattened work roll, whose computation follows below Eq. 4

Roll (bite) angle [rad]

$$\alpha = \sqrt{\frac{\Delta h}{r'}}$$ Eq. 5

Neutral angle [rad]

$$\alpha_n = \frac{1}{x} \cdot \tan\left( \frac{1}{2 \cdot x} \cdot \left( \frac{\pi}{4} \cdot \ln\left( \frac{h_2}{h_1} \right) + x \cdot \arctan(x \cdot a) \right) \right)$$
where $x = \sqrt{\frac{r'}{h_2}}$ Eq. 6

Neutral thickness [mm]

$$h_n = h_2 + r' \cdot \alpha_n^2$$ Eq. 7

Geometric roll force factor [mm$^2$]

$$ff = w \cdot r' \cdot \left( \frac{\pi}{2 \cdot x} \cdot \arctan(xx) - \pi \cdot \frac{\alpha}{4} - \ln\left(\frac{h_n}{h_2}\right) + \frac{1}{2} \cdot \ln\left(\frac{h_1}{h_2}\right)\right) \qquad \text{Eq. 8}$$

$$\text{where} \quad xx = \sqrt{\frac{\varepsilon}{1-\varepsilon}}$$

Reduction of roll force, if tensions are applied [N]

$$F_{tens} = w \cdot l_d \cdot \left( \left(1 - \frac{\alpha_n}{\alpha}\right) \cdot tens_b + \frac{\alpha_n}{\alpha} \cdot tens_f \right) \qquad \text{Eq. 9}$$

Total strain [1]

$$\varphi_{tot} = \ln\left(\frac{h_{trb}}{h_2}\right) \qquad \text{Eq. 10}$$

Average strain rate [1/s]

$$\dot{\varphi} = \frac{v_w \cdot \ln\left(\frac{h_1}{h_2}\right)}{l_d} \cdot 10^3 \qquad \text{Eq. 11}$$

Average yield stress for roll force [N/mm²] (cf. chapter 'Material equation')

$$k_f^F = k_f^F\left(T, \dot{\varphi}, \varphi_{tot}, i_{sgcl}, i_{stno}\right) \qquad \text{Eq. 12}$$

Roll force [kN]

$$F = \left(k_f^F \cdot ff - F_{tens}\right) \cdot 10^{-3} \qquad \text{Eq. 13}$$

Radius of flattened work roll (HITCHCOCK's formula) [mm]

$$r' = r \cdot \left(1 + \frac{c \cdot F \cdot 10^3}{w \cdot \Delta h}\right)$$

$$\text{where} \quad c = \frac{16 \cdot \left(1 - \nu^2\right)}{\pi \cdot E}$$ Eq. 14

Additional torque, if tensions are applied and due to friction [N·mm]

$$TOR_{tens} = w \cdot \left(r' + \frac{h_2}{2}\right) \cdot \left(tens_b \cdot h_1 - tens_f \cdot h_2\right) + 2 \cdot \frac{r_{bear} \cdot r \cdot F \cdot 10^3 \cdot \mu}{r_{bu}}$$ Eq. 15

Geometric roll torque factor [mm³]

$$tt = 2 \cdot w \cdot r \cdot r' \cdot \left(\frac{\alpha}{2} - \alpha_n\right)$$ Eq. 16

Average yield stress for roll torque [N/mm²] (cf. chapter 'Material equation')

$$k_f^T = k_f^T\left(k_f^F, i_{sgcl}\right)$$ Eq. 17

Roll torque [kNm]

$$TOR = \left(k_f^T \cdot tt + TOR_{tens}\right) \cdot 10^{-6}$$ Eq. 18

Entry speed [m/s]

$$v_{entry} = \frac{v_w \cdot h_n}{h_1}$$ Eq. 19

Exit speed [m/s]

$$v_{exit} = \frac{v_w \cdot h_n}{h_2}$$ Eq. 20

Forward slip [%]

$$slip_f = \frac{v_{exit} - v_w}{v_w} \cdot 100 = \left( \frac{h_n}{h_2} - 1 \right) \cdot 100 \qquad \text{Eq. 21}$$

Backward slip [%]

$$slip_b = \frac{v_w - v_{entry}}{v_w} \cdot 100 = \left( 1 - \frac{h_n}{h_1} \right) \cdot 100 \qquad \text{Eq. 22}$$

**Internal values**

none

**Calculation sequence**

The calculation for Eq. 1 - Eq. 3 and Eq. 15 - Eq. 22 is done straight forward. As the radius of the flattened work roll is a function of the roll force and vice versa

$$\left. \begin{array}{l} r' = f(F) \\ F = g(r') \end{array} \right\} \Rightarrow r' = (f \circ g)(r')$$

an iteration for Eq. 4 - Eq. 14 has to be carried out to make roll force and flattened work roll radius compatible

$$r'_o = r$$
$$r'_{i+1} = f\left(g(r'_i)\right) \quad i = 0,1,2,\ldots$$
Termination test
$$\left| \frac{r'_i - r'_{i+1}}{r'_{i+1}} \cdot 100 \right| < \varepsilon_{tol} (\approx 1\%) \quad \vee \quad i \geq i_{\max} (\approx 10)$$

**References**

[1] R.B. SIMS: The calculation of roll force and torque in hot rolling mills, Proc. Inst. Mech. Eng. (1954) 191-200.

[2] J.H. HITCHCOCK: Rock neck bearings, ASME (1935).

# 4.3 Material Equation

### Description

The material law describes the behaviour of the material in parameterized form under the different circumstances. It is used to calculate the average yield stress of the strip material depending on the steel grade, the temperature, the speed, the total strain and the recrystallization effect.

### Input values

| | |
|---|---|
| $i_{sgcl}$ | Steel grade class index [1] |
| $i_{stno}$ | Stand number [1] |
| $T$ | Strip entry temperature [°F -> °C] |
| $\dot{\varphi}$ | Average strain rate [1/s] |
| $\varphi_{tot}$ | Total strain [1] |

### Output values

| | |
|---|---|
| $k_f^F$ | Average yield stress roll force [N/mm² -> psi] |
| $k_f^T$ | Average yield stress roll torque [N/mm² -> psi] |

### Submodels

none

### Model equations:

Yield stress formula for roll force:

$$k_f^F = k_{f0} \cdot e^{-m_1 \cdot T} \cdot \dot{\varphi}^{m_2} \cdot \varphi_{tot}^{m_3} \cdot m_4$$

where

$$\mathrm{k}_{f0} = \mathrm{k}_{f0}\left(i_{sgcl}\right)$$

$$\mathrm{m}_1 = m_1(i_{sgcl})$$
$$\mathrm{m}_2 = m_2(i_{sgcl})$$
$$\mathrm{m}_3 = m_3(i_{sgcl})$$
$$\mathrm{m}_4 = m_4(i_{sgcl}, i_{stno})$$

Yield stress formula for roll torque:

$$k_f^T = \eta \cdot k_f^F$$

where

$$\eta = \eta(i_{sgcl}, i_{stno})$$

### Internal values

| | |
|---|---|
| $k_{f0}$ | general coefficient material law [1] |
| $m_1$ | temperature coefficient material law [1] |
| $m_2$ | speed coefficient material law [1] |
| $m_3$ | strain coefficient material law [1] |
| $m_4$ | recrystallization coefficient material law [1] |
| $\eta$ | roll torque coefficient [1] |

### Calculation sequence

The calculation is done straight forward.

## 4.4 Roll Gap Temperature Model

### Description

The temperature model for the roll gap is due to PAWELSKI and describes the temperature variation of the strip during the reduction in a single stand. The model is used to calculate this temperature variation. It takes into account the temperature increase by the deformation work in the roll gap and the temperature loss by heat conduction from the strip to the work roll. The calculation of the temperature variation is done straightforward.

### Input values

Strip data

| | |
|---|---|
| $T_1$ | Entry temperature [°F -> °C] |
| $h_1$ | Entry thickness [in. -> mm] |
| $h_2$ | Exit thickness [in. -> mm] |
| $w$ | Width [in. -> mm] |
| $c_{strip}(T_1)$ | Specific heat capacity [Btu/lb/°F -> J/kg/K] |
| $\lambda_{strip}(T_1)$ | Thermal conductivity [Btu·in./s/ft²/°F -> W/m/K] |
| $\rho_{strip}(T_1)$ | Density [lb/in.³ -> kg/m³] |

Work roll data

| | |
|---|---|
| $v_w$ | Rolling speed [ft/min -> m/s] |
| $T_w$ | Average temperature of kernel [°F -> °C] |
| $c_w$ | Average specific heat capacity [Btu/lb/°F -> J/kg/K] |
| $\lambda_w$ | Average thermal conductivity [Btu·in./s/ft²/°F -> W/m/K] |
| $\rho_w$ | Average density [lb/in.³ -> kg/m³] |

Scale layer data

$h_{scale}$ Average thickness [in. -> mm]

$c_{scale}$ Average specific heat capacity [Btu/lb/°F -> J/kg/K]

$\lambda_{scale}$ Average thermal conductivity [Btu·in./s/ft²/°F -> W/m/K]

$\rho_{scale}$ Average density [lb/in.³ -> kg/m³]

Data from roll force model

$r'$ Flattened work roll radius [in. -> mm]

$h_n$ Neutral thickness [in. -> mm]

$l_d$ Roll contact length [in. -> mm]

$F$ Roll force [lb -> kN]

Adjustments

$cor_{deform}$ Corrector deformation work [1]

$cor_{trans}$ Corrector heat transision strip-roll [1]

Adapters

$cor_1$ Adapter [1]

**Output values**

$T_2$ Exit temperature [°C -> °F]

**Submodels**

Roll force model

**Model equations:**

Volume in roll gap per time unit [mm³/s]:

$$V_t = w \cdot h_n \cdot v_w \cdot 10^3$$

Contact time [s]:

$$t_c = \frac{l_d}{v_w} \cdot 10^{-3}$$

Temperature rise caused by deformation [°C]:

$$\Delta T_{def} = cor_1 \cdot cor_{deform} \cdot \frac{F \cdot \ln\left(\frac{h_1}{h_2}\right)}{w \cdot l_d \cdot \rho_{strip}(T_1) \cdot c_{strip}(T_1)} \cdot 10^9$$

Heat penetration coefficient for the strip $\left[\mathrm{J/m^2/K/\sqrt{s}}\right]$:

$$b_{strip} = \sqrt{\lambda_{strip}(T_1) \cdot \rho_{strip}(T_1) \cdot c_{strip}(T_1)}$$

Heat penetration coefficient for the scale $\left[\mathrm{J/m^2/K/\sqrt{s}}\right]$:

$$b_{scale} = \sqrt{\lambda_{scale} \cdot \rho_{scale} \cdot c_{scale}}$$

Heat penetration coefficient for the work roll $\left[\mathrm{J/m^2/K/\sqrt{s}}\right]$:

$$b_w = \sqrt{\lambda_w \cdot \rho_w \cdot c_w}$$

Lower bound for the heat transition coefficient $\left[\mathrm{W/m^2/K}\right]$:

$$k_{\min} = \frac{2 \cdot b_w \cdot b_{scale}}{\sqrt{\pi} \cdot (b_w + b_{scale}) \cdot \sqrt{t_c}}$$

Parameter for the heat transition coefficient [1]:

$$z = \frac{2 \cdot \lambda_{scale} \cdot \sqrt{t_c}}{b_{strip} \cdot h_{scale}} \cdot 10^3$$

Heat transition coefficient $\left[\mathrm{W / m^2 / K}\right]$:

$$k = \max\left( \frac{b_{strip}}{2 \cdot \sqrt{t_c}} \cdot \left( \frac{e^{z^2}}{z} \cdot \left(1 - \Phi(z)\right) - \frac{1}{z} + \frac{2}{\sqrt{\pi}} \right), k_{\min} \right)$$

where

$$\Phi(\mathrm{z}) = \frac{2}{\sqrt{\pi}} \cdot \int_0^z e^{-t^2} dt \quad , z \geq 0$$

The following approximation is applicable for $z > 0$

$$\frac{e^{z^2}}{z} \cdot \left(1 - \Phi(z)\right) \approx \frac{1}{z} \cdot \sqrt{\frac{2}{\pi}} \cdot \left(a_1 \cdot X + a_2 \cdot X^2 + a_3 \cdot X^3 + a_4 \cdot X^4 + a_5 \cdot X^5\right)$$

where

$$X = \frac{1}{1 + b \cdot \sqrt{2} \cdot z}$$

$$b = 0.2316419$$

$$a_1 = 0.31938153$$

$$a_2 = -0.356563782$$

$$a_3 = 1.781477937$$

$$a_4 = -1.821255978$$

$$a_5 = 1.330274429$$

Temperature drop caused by conduction from material to work roll [°C]:

$$\Delta T_{con} = cor_1 \cdot cor_{trans} \cdot \frac{2 \cdot k \cdot l_d \cdot w \cdot \left(T_1 - T_w\right)}{V_t \cdot \rho_{strip}\left(T_1\right) \cdot c_{strip}\left(T_1\right)} \cdot 10^3$$

Difference between exit and entry temperature [°C]:

$$\Delta T = \Delta T_{def} - \Delta T_{con}$$

Exit temperature [°C]:

$$T_2 = T_1 + \Delta T$$

### Internal values

none

### Calculation sequence

The calculation is done straight forward.

### References

[1] O. PAWELSKI: Berechnung des Temperaturverlaufs in der Fertigstraße einer Warmbreitbandstraße, Stahl und Eisen 89 (1969) 1146-1150.

[2] O. PAWELSKI: Berechnung der Wärmedurchgangszahl für das Warmwalzen und Schmieden, Arch. Eisenhüttenwesen 40 (1969) 821-827.

## 4.5 Radiation Temperature Model

### Description

The radiation temperature model describes the temperature drop of the strip during transportation on uncovered roller tables without water on the strip surface. This is applicable e.g. between the finishing stands and during the transportation of the strip from the roughing stand to the heat cover in front of the finishing stand. The model is based on the heat transfer between the strip surface and the environment caused by radiation. The calculation is done by the iterative solution of an ordinary differential equation for the mean strip temperature and the iterative solution of a system of two non-linear equations for the boundary conditions at top and bottom. As simplification a parabolic temperature distribution along the strip thickness is assumed.

### Input values

| | |
|---|---|
| $T_{entry}$ | Mean temperature at start of radiation [°F -> K] |
| $dur$ | Duration of radiation [s] |
| $h$ | Strip thickness [in. -> m] |
| $\lambda = \lambda(\vartheta)$ | Thermal conductivity (temp. dep.) [Btu·in./s/ft$^2$/°F -> W/m/K] |
| $\rho = \rho(\vartheta)$ | Density (temp. dependent) [lb/in.$^3$ -> kg/m$^3$] |
| $c = c(\vartheta)$ | Specific heat capacity (temp. dependent) [Btu/lb/°F -> J/kg/K] |
| $\sigma$ | Stefan-Boltzmann constant [Btu/in.$^2$/h/°F$^4$ -> J/s/m$^2$/K$^4$] |
| $\varepsilon_{top}$ | Emissivity top [1] |
| $\varepsilon_{bot}$ | Emissivity bottom [1] |
| $T_{amb,top}$ | Ambient temperature top [°F -> K] |
| $T_{amb,bot}$ | Ambient temperature bottom [°F -> K] |

### Adjustments

| | |
|---|---|
| $cor_{Rad}$ | Corrector for radiation [1] |

$cor_{Cover}$ Corrector for table cover influence [1]

**Adapter**

$cor_1$ Corrector deformation work [1]

**Output values**

$T_{exit}$ Mean temperature at the end of radiation [K -> °F]

**Submodels**

none

**Model equations:**

Assumption of parabolic temperature distribution along the thickness:

$$T(z,t) = T(z) = a_0 + a_1 \cdot z + a_2 \cdot z^2 = a_0(t) + a_1(t) \cdot z + a_2(t) \cdot z^2$$

where

| | |
|---|---|
| $T = T(z,t) = T(z)$ | Temperature distribution $[\mathrm{K}]$ |
| $-h/2 \le z \le +h/2$ | Thickness coordinate $[\mathrm{m}]$ |
| $t \ge 0$ | Time coordinate $[\mathrm{s}]$ |
| $a_i = a_i(t), i = 0,1,2$ | Time variant coefficients of quadratic $[1]$ |

Ordinary differential equation for the mean temperature:

$$\frac{d\overline{T}}{dt} = -\underbrace{\frac{\varepsilon_{top}\cdot\sigma}{c\cdot\rho\cdot h}}_{K_{top}}\cdot\left(\left(\overline{T}+\Delta T_{top}\right)^4 - T^4_{amb,top}\right) - \underbrace{\frac{\varepsilon_{bot}\cdot\sigma}{c\cdot\rho\cdot h}}_{K_{bot}}\cdot\left(\left(\overline{T}+\Delta T_{bot}\right)^4 - T^4_{amb,bot}\right) \text{ Eq. 1}$$

$$\frac{d\overline{T}}{dt} = -\underbrace{cor_{\mathrm{cover}}\cdot\frac{\varepsilon_{top}\cdot\sigma}{c\cdot\rho\cdot h}}_{K_{top}}\cdot\left(\left(\overline{T}+\Delta T_{top}\right)^4 - T^4_{amb,top}\right) - \underbrace{\frac{\varepsilon_{bot}\cdot\sigma}{c\cdot\rho\cdot h}}_{K_{bot}}\cdot\left(\left(\overline{T}+\Delta T_{bot}\right)^4 - T^4_{amb,bot}\right) \text{ if tablecover is c}$$

where

$$\overline{T} = \overline{T}(t) = \frac{1}{h}\cdot\int_{-h/2}^{+h/2} T(z,t)\,dz \qquad \text{Mean temperature } [\mathrm{K}]$$

$$\Delta T_{top} = \Delta T_{top}(t) = T\left(+\frac{h}{2}\right) - \overline{T} = T\left(+\frac{h}{2},t\right) - \overline{T}(t) \qquad \text{Correction term top } [\mathrm{K}]$$

$$\Delta T_{bot} = \Delta T_{bot}(t) = T\left(-\frac{h}{2}\right) - \overline{T} = T\left(-\frac{h}{2},t\right) - \overline{T}(t) \qquad \text{Correction term bottom } [\mathrm{K}]$$

Boundary conditions:

$$\left.\begin{aligned} -\lambda\cdot\frac{dT}{dz}\left(+\frac{h}{2}\right) &= \varepsilon_{top}\cdot\sigma\cdot\left(T\left(+\frac{h}{2}\right)^4 - T^4_{amb,top}\right) \\ +\lambda\cdot\frac{dT}{dz}\left(-\frac{h}{2}\right) &= \varepsilon_{bot}\cdot\sigma\cdot\left(T\left(-\frac{h}{2}\right)^4 - T^4_{amb,bot}\right) \end{aligned}\right\}$$

χ

$$\left.\begin{aligned} -\lambda\cdot\left(a_1 + a_2\cdot h\right) &= \varepsilon_{top}\cdot\sigma\cdot\left(\left(\overline{T} + a_1\cdot\frac{h}{2} + a_2\cdot\frac{h^2}{6}\right)^4 - T^4_{amb,top}\right) \\ +\lambda\cdot\left(a_1 - a_2\cdot h\right) &= \varepsilon_{bot}\cdot\sigma\cdot\left(\left(\overline{T} - a_1\cdot\frac{h}{2} + a_2\cdot\frac{h^2}{6}\right)^4 - T^4_{med,bot}\right) \end{aligned}\right\}\text{Eq. 2}$$

The numerical solution of Eq. 1 can be done by TAYLOR expansion:

$$\overline{T}(t+\Delta t) \approx \overline{T}(t) + \frac{d\overline{T}}{dt}(t)\cdot\Delta t + \frac{d^2\overline{T}}{dt^2}(t)\cdot\frac{\Delta t^2}{2!}$$

where

$$\frac{d^2\overline{T}}{dt^2} = 4\cdot\left(K_{top}\cdot\left(\overline{T}+\Delta T_{top}\right)^3 + K_{bot}\cdot\left(\overline{T}+\Delta T_{bot}\right)^3\right)\cdot\frac{d\overline{T}}{dt}$$

$$\Downarrow \quad \left(t \leftrightarrow i-1,\ t+\Delta t \leftrightarrow i\right)$$

$$\overline{T}_i = \overline{T}_{i-1} + cor_1\cdot cor_{rad}\cdot\left(\left(\frac{d\overline{T}}{dt}\right)_{i-1}\cdot\Delta t + \left(\frac{d^2\overline{T}}{dt^2}\right)_{i-1}\cdot\frac{\Delta t^2}{2}\right) \quad \text{Eq. 3}$$

### Internal values

none

### Calculation sequence

The calculation is done by iteration:

$$\Delta t = \frac{dur}{N}, \qquad N \text{ (large enough) Number of time intervals}$$

$$\overline{T}_0 = T_{entry}, \Delta T_{top,0} = \Delta T_{bot,0} = 0$$

FOR $i = 1,\dots,N$

Compute $\overline{T}_i = f\left(\overline{T}_{i-1}, \Delta T_{top,i-1}, \Delta T_{bot,i-1}, \Delta t\right)$ acc. Eq. 3

Compute $a_{1,i}, a_{2,i}$ as solution of Eq. 2 (e.g. by NEWTON - RAPHSON)

$$\Delta T_{top,i} = +a_{1,i}\cdot\frac{h}{2} + a_{2,i}\cdot\frac{h^2}{6}$$

$$\Delta T_{bot,i} = -a_{1,i}\cdot\frac{h}{2} + a_{2,i}\cdot\frac{h^2}{6}$$

$$T_{exit} = \overline{T}_N$$

### References

[1] G. UETZ et al: Influencing the formation of the steel structure by suitable temperature control in the run-out section of hot-strip mills, steel research 62(1991)No.5,216-222.

# 4.6 Descaling and Cooling Model

## Description

The descaling and cooling model describes the temperature drop of the strip during contact with water. This takes place in the descaler in front of finishing stand F1 and the interstand cooling devices between the finishing stands F1 to F4. The model is based on the heat transfer between the strip surface and the coolant caused by convection. The calculation is done by the iterative solution of an ordinary differential equation for the mean strip temperature and the solution of a system of two linear equations for the boundary conditions at top and bottom. As simplification a parabolic temperature distribution along the strip thickness is assumed.

## Input values

$T_{entry}$ Mean temperature at the start of cooling [°F -> K]

$dur$ Duration of cooling [s]

$h$ Strip thickness [in. -> m]

$\lambda = \lambda(\vartheta)$ Thermal conductivity (temp. dependent) [Btu·in./s/ft²/°F -> W/m/K]

$\rho = \rho(\vartheta)$ Density (temp. dependent) [lb/in.³ -> kg/m³]

$c = c(\vartheta)$ Specific heat capacity (temp. dependent) [Btu/lb/°F -> J/kg/K]

$\alpha_{top} = \alpha_{top}(V_w, \partial_{surf})$ Heat transfer coeff. top (depending on water flow rate and surface temperature) [Btu/ft²/h/°F -> W/m²/K]

$\alpha_{bot} = \alpha_{bot}(V_w, \partial_{surf})$ Heat transfer coeff. bottom (depending on water flow rate and surf. temperature [Btu/ft²/h/°F -> W/m²/K]

$T_{water}$ Water temperature [°F -> K]

## Output values

$T_{exit}$ Mean temperature at the end of cooling [K -> °F]

### Submodels

none

### Model equations:

Assumption of parabolic temperature distribution along the thickness:

$$T(z,t) = T(z) = a_0 + a_1 \cdot z + a_2 \cdot z^2 = a_0(t) + a_1(t) \cdot z + a_2(t) \cdot z^2$$

where

| | |
|---|---|
| $T = T(z,t) = T(z)$ | Temperature distribution $[\mathrm{K}]$ |
| $-h/2 \le z \le +h/2$ | Thickness coordinate $[\mathrm{m}]$ |
| $t \ge 0$ | Time coordinate $[\mathrm{s}]$ |
| $a_i = a_i(t), i = 0,1,2$ | Time variant coefficients of quadratic $[1]$ |

Ordinary differential equation for the mean temperature:

$$\frac{d\overline{T}}{dt} = -\underbrace{\frac{\alpha_{top}}{c \cdot \rho \cdot h}}_{K_{top}} \cdot \left(\overline{T} + \Delta T_{top} - T_{water}\right) - \underbrace{\frac{\alpha_{bot}}{c \cdot \rho \cdot h}}_{K_{bot}} \cdot \left(\overline{T} + \Delta T_{bot} - T_{water}\right) \quad \text{Eq. 1}$$

where

| | |
|---|---|
| $\overline{T} = \overline{T}(t) = \frac{1}{h} \cdot \int_{-h/2}^{+h/2} T(z,t)dz$ | Mean temperature $[\mathrm{K}]$ |
| $\Delta T_{top} = \Delta T_{top}(t) = T\left(+\frac{h}{2}\right) - \overline{T} = T\left(+\frac{h}{2},t\right) - \overline{T}(t)$ | Correction term top $[\mathrm{K}]$ |
| $\Delta T_{bot} = \Delta T_{bot}(t) = T\left(-\frac{h}{2}\right) - \overline{T} = T\left(-\frac{h}{2},t\right) - \overline{T}(t)$ | Correction term bottom $[\mathrm{K}]$ |

Boundary conditions:

$$\left.\begin{aligned}-\lambda\cdot\frac{dT}{dz}\left(+\frac{h}{2}\right)&=\alpha_{top}\cdot\left(T\left(+\frac{h}{2}\right)-T_{water}\right)\\+\lambda\cdot\frac{dT}{dz}\left(-\frac{h}{2}\right)&=\alpha_{bot}\cdot\left(T\left(-\frac{h}{2}\right)-T_{water}\right)\end{aligned}\right\}$$

$$\chi$$

$$\left.\begin{aligned}-\lambda\cdot\left(a_1+a_2\cdot h\right)&=\alpha_{top}\cdot\left(\overline{T}+a_1\cdot\frac{h}{2}+a_2\cdot\frac{h^2}{6}-T_{water}\right)\\+\lambda\cdot\left(a_1-a_2\cdot h\right)&=\alpha_{bot}\cdot\left(\overline{T}-a_1\cdot\frac{h}{2}+a_2\cdot\frac{h^2}{6}-T_{water}\right)\end{aligned}\right\}\text{Eq. 2}$$

The numerical solution of Eq. 1 can be done by TAYLOR expansion:

$$\overline{T}(t+\Delta t)\approx\overline{T}(t)+\frac{d\overline{T}}{dt}(t)\cdot\Delta t+\frac{d^2\overline{T}}{dt^2}(t)\cdot\frac{\Delta t^2}{2!}$$

where

$$\frac{d^2\overline{T}}{dt^2}=\left(K_{top}+K_{bot}\right)\cdot\frac{d\overline{T}}{dt}$$

$$\Downarrow\quad\left(t\leftrightarrow i-1,\ \ t+\Delta t\leftrightarrow i\right)$$

$$\overline{T}_i=\overline{T}_{i-1}+\left(\frac{d\overline{T}}{dt}\right)_{i-1}\cdot\Delta t+\left(\frac{d^2\overline{T}}{dt^2}\right)_{i-1}\cdot\frac{\Delta t^2}{2}\quad\text{Eq. 3}$$

### Internal values

none

### Calculation sequence

The calculation is done by iteration:

$$\Delta t = \frac{dur}{N}, \qquad N \text{ (large enough) Number of time intervals}$$

$$\overline{T}_0 = T_{entry}, \Delta T_{top,0} = \Delta T_{bot,0} = 0$$

FOR $\quad i = 1, \ldots, N$

Compute $\overline{T}_i = f\left(\overline{T}_{i-1}, \Delta T_{top,i-1}, \Delta T_{bot,i-1}, \Delta t\right)$ acc. Eq. 3

Compute $a_{1,i}, a_{2,i}$ as solution of Eq. 2

$$\Delta T_{top,i} = +a_{1,i} \cdot \frac{h}{2} + a_{2,i} \cdot \frac{h^2}{6}$$

$$\Delta T_{bot,i} = -a_{1,i} \cdot \frac{h}{2} + a_{2,i} \cdot \frac{h^2}{6}$$

$$T_{exit} = \overline{T}_N$$

## References

[1] G. UETZ et al: Influencing the formation of the steel structure by suitable temperature control in the run-out section of hot-strip mills, steel research 62(1991)No.5,216-222.

## 4.7 Temperature and Speed Calculation

### Description

The threading speed for the strip head is selected in such a way, that the finishing temperature is met as accurate as possible. This submodel is an integral part of the rolling strategy.

### Input values

$L_{h_i,x}$ Strip segment [ft -> m]

$T^*_{R,x}$ Measured roughing stand temperature [°F -> °C]

$T_{F,tar}$ Target finishing temperature [°F -> °C]

$T_{HC\_tail\_last\_strip}$ Heat cover temperature after tail last strip [°F -> °C]

$\Delta t_{HC\_head\_to\_tail}$ Time tail to head [s]

### Output values

$v_{R,F6}$ Rolling speed F6 [m/s -> ft/min]

### Submodels

$T_{RG}$ Roll gap temperature model

$T_{RAD}$ Radiation temperature model

$T_{WC}$ Descaling and interstand cooling model

$T_{HCSt}$ Heat cover strip temperature model

$T_{HC}$ Heat cover temperature model

Mass flow considerations

### Model equations

Transferbar temperature at roughing stand for a certain strip segment especially for the head end:

$$T_{R,x}^{*} = T_{R}^{*}(L_{h_0,x}, z) \quad \text{with } \frac{\partial T_R}{\partial z} = 0$$

Transfer bar temperature at the entry of the heat cover:

$$T_{HCEN,x} = T_{HCEN}(L_{h_0,x}) = T_{RAD}(T_{R,x}^{*}, \Delta t_{TR-HCEN,x})$$

Heat cover temperature when strip head enters the heat cover:

$$T_{HC,0} = T_{HC}(L_{h_0,x} = 0) = T_{HC\_no\_strip}(T_{HC\_tail\_last\_strip}, \Delta t_{HC\_head\_to\_tail})$$

Heat cover temperature when strip segment enters the heat cover:

$$T_{HC,x} = T_{HC}(L_{h_0,x}) = T_{HC\_with\_strip}(T_{HC,0}, \Delta t_{HC\_heat,x})$$

Transfer bar temperature at the exit of the heat cover:

$$T_{HCEX,x} = T_{HCEX}(L_{h_0,x}) = T_{HCSt}(T_{HCEN,x}, T_{HC,x}, \Delta t_{HC,x})$$

Transfer bar temperature before descaler:

$$T_{DESEN,x} = T_{DESEN}(L_{h_0,x}) = T_{RAD}(T_{HCEX,x}, \Delta t_{HCEX-DES,x})$$

Transfer bar temperature after descaler:

$$T_{DESEX,x} = T_{DESEX}(L_{h_0,x}) = T_{WC}(T_{DESEN,x}, \Delta t_{DES,x})$$

Transfer bar temperature before finishing stand F1:

$$T_{F1EN,x} = T_{F1EN}(L_{h_0,x}) = T_{RAD}(T_{DESEX,x}, \Delta t_{DES-F1,x})$$

Strip temperature after a certain finishing stand:

$$T_{FiEX,x} = T_{FiEX}(L_{h_i,x}) = T_{RG}(T_{FiEN,x}, v_{R,F6})$$

Strip temperature before a certain finishing stand with interstand cooling:

$$T_{FiEN,x} = T_{FiEN}(L_{h_i,x}) = T_{WC}(T_{F(i-1)EX,x}, \Delta t_{F(i-1)EX-FiEN,x}, v_{R,F6})$$

Strip temperature before a certain finishing stand without interstand cooling:

$$T_{FiEN,x} = T_{FiEN}(L_{h_i,x}) = T_{RAD}(T_{F(i-1)EX,x}, \Delta t_{F(i-1)EX-FiEN,x}, v_{R,F6})$$

Strip temperature at finishing temperature measuring device:

$$T_{F,x} = T_F(L_{h_6,x}) = T_{RAD}(T_{F6,x}, \Delta t_{F6EX-FT,x}, v_{R,F6})$$

Calculation of rolling speed $v_{R,F6}$ for strip head that target finishing temperature is achieved:

$$T_{F,x}(v_{R,F6}, T^*_{R,x}) - T_{F,tar} = 0$$

### Internal values

| | |
|---|---|
| $z$ | Coordinate in strip thickness direction [in. -> mm] |
| $\Delta t$ | Transportation times [s] |

### Calculation sequence

The calculation is done straight forward.

### References

none

## 4.8 Width Model

### Description

The width model calculates the increase in width of the material within the finishing mill. and the width reduction by strip tension. In the finishing mill only flat passes are applied to the material. Therefore the spreading is described by a lateral spreading model while the tension influence is described by a heuristic model.

As no measured transfer bar width is available, the transfer bar width is calculated by aid of the slab width and the rolling practice in the rougher and the various edging passes. Besides the lateral spreading of material the dog bone spreading must be considered in this area. This dog bone spreading model describes the increase in width when an edging pass is followed by a flat pass.

### Input values

| | |
|---|---|
| $w_{slab}$ | Slab width [in. -> mm] |
| $h_{slab}$ | Slab thickness [in. -> mm] |
| $n_{rou}$ | Number of passes at Roughing mill [1] |
| $\left(h_i^{rou}\right)_{i=1}^{n_{rou}}$ | Exit thicknesses at Roughing mill [in. -> mm] |
| $\left(w_i^{edger}\right)_{i=0}^{n_{rou}}$ | Edging widths [in. -> mm], if edging pass was performed, -1 else ($i$ = 0 ... primary edger) |
| $n_{fin}$ | Number of passes at Finishing mill (in case of inactive stands) [1] |
| $\left(h_i^{fin}\right)_{i=1}^{n_{fin}}$ | Exit thicknesses at Finishing mill [in. -> mm] |
| $r_{rou}$ | Average work roll radius at Roughing mill [in. -> mm] |
| $r_{fin}$ | Average work roll radius at Finishing mill [in. -> mm] |
| $r_{edger}$ | Average work roll radius at Edger [in. -> mm] |
| $r_{edger}^{prim}$ | Average work roll radius at primary Edger [in. -> mm] |
| $i_{sgcl}$ | Steel grade class index [1] |

$tens_{f,stno}$ Specific tension forward [psi ->N/mm^2]

$k_{ff,stno}$ Yield stress rollforce [psi ->N/mm^2]

$a_{sg}$ tension factor, steel dependend [in -> mm]

**Output values**

$(w_i)_{i=1}^{n_{rou}}$ Exit widths at Roughing Mill [mm -> in.]

$(w_i)_{i=1}^{n_{fin}}$ Exit widths at Finishing Mill [mm -> in.]

**Submodels**

none

**Model equations:**

Lateral spread after reduction in thickness:

$$\Delta h = h_1 - h_2$$
$$l_d = \sqrt{r \cdot \Delta h}$$
$$m = \frac{w_1}{h_1}$$
$$S_W = \exp\left(-1.64 \cdot m^{0.376} \cdot \left(\frac{w_1}{l_d}\right)^{0.016 \cdot m} \cdot \left(\frac{h_1}{r}\right)^{0.015 \cdot m}\right)$$
$$\Delta w_{lat} = w_1 \cdot \left(\left(\frac{h_1}{h_2}\right)^{S_W} - 1\right)$$

where

$h_1$ Thickness before thickness reduction [mm]

$h_2$ Thickness after thickness reduction [mm]

| | |
|---|---|
| $r$ | Radius of work roll [mm] |
| $w_1$ | Width before thickness reduction [mm] |
| $\Delta w_{lat}$ | Increase in width [mm] |

Additional spread due to bulging if a vertical edger pass was carried out before the flat pass:

$$d_e = w_0 - w_1$$

$$b = \exp\left(-1.877 \cdot \left(\frac{d_e}{w_0}\right)^{0.063} \cdot \left(\frac{h_1}{r_e}\right)^{0.441} \cdot \left(\frac{r_e}{w_0}\right)^{0.989} \cdot \left(\frac{w_0}{w_1}\right)^{7.591}\right)$$

$$\Delta w_{bul} = b \cdot d_e \cdot \left(1 + \frac{\Delta w_{lat}}{w_1}\right)$$

where

| | |
|---|---|
| $\Delta R_{wTherm}$ | Width before edging [mm] |
| $w_1$ | Width after edging [mm] |
| $h_1$ | Thickness before thickness reduction [mm] |
| $r_e$ | Radius of edger work roll [mm] |
| $\Delta s$ | Increase in width due to bulging [mm] |

Width reduction by strip tension:

$$C_{tot} = \frac{1}{1/C_{MS} + 1/C_{RS}}$$

where

$\Delta s = F_R / C_{tot} + 4 \cdot \Delta R_{WTherm} - 2 \cdot \Delta R_{WWear} + \delta_{corr}$ Decrease in width due to strip tension [mm]

**Internal values**

none

### Calculation sequence

The calculation is done straight forward

### References

[1] V.B. GINZBURG: Width control in hot strip mills, Iron and Steel Engineer (1991) 25-39.

[2] T. SHIBAHARA et al: Edger set-up model at roughing train in hot strip mill, Tetsu-to-Hagane (1981) 2509-2515.

# 4.9 Gauge Meter Model

### Description

The gauge meter model describes the behaviour of the mill stand under load. The gauge meter model is used to calculate the difference between the loaded and the unloaded rolling gap taking into consideration the following effects

- Strip thickness
- Measured mill stretch curve
- Calibration point
- Roll set deformation
- Thermal expansion of work roll
- Wear of work roll

### Input values

General

| | |
|---|---|
| $F_R$ | Rolling Force [lb -> kN] |
| $C_{MS}$ | Mill modulus taken from mill stretch curve [lb/in. -> kN/mm] |
| $C_{RS}$ | Mill modulus due to roll set deformation [lb/in. -> kN/mm] |
| $\Delta R_{wTherm}$ | Thermal work roll crown [in. -> mm] |
| $\Delta R_{wwear}$ | Work roll crown due to wear [in. -> mm] |
| $\delta_{RS}$ | Deformation of roll set [in. -> mm] |

Adapter

$\delta_{corr}$ Screw down position correction [in. -> mm]

### Output values

$\Delta s$ Correction of screw down position [mm -> in.]

$C_{tot}$ Total mill stretch [kN/mm -> lb/in.]

### Model equation

Total mill modulus (mill stretch):

$$C_{tot} = \frac{1}{1/C_{MS} + 1/C_{RS}}$$

Total correction of screw down position:

$$\Delta s = F_R / C_{tot} + 4 \cdot \Delta R_{WTherm} - 2 \cdot \Delta R_{WWear} + \delta_{corr}$$

### Internal values

none

### Calculation Sequence

The calculation is done straight forward.

### References

none

## 4.10 Roll Wear Model

### Description

The roll wear model is used to determine the reduction of the work roll diameter due to roll wear between the strip and the work roll. The used model is based on an empirical formula.

### Input values

General

- $F_R$ Rolling Force [lb -> N]
- $w$ Strip width [in. -> mm]
- $L_{St}$ Strip length [ft -> mm]
- $C$ Pressure coefficient for contact area between work and backup roll [1]

Adapter

- $k_{Wear}$ Wear coefficient [mm/N]

### Output values

- $\Delta R_{WWear}$ Actual work roll wear [mm -> in.]

### Submodels

none

### Model equations

Roll wear:

$$\Delta R_{WWear}(z) = L_{St} \cdot (p_{WB}(z) + p_{WSt}(z)) \cdot k_{Wear}$$
$$\text{for } -L_B / 2 \le z \le L_B / 2$$

Load between work and backup roll:

$$p_{WB}(z) = \frac{F_R}{w} \cdot (C - 12 \cdot (C-1)(\frac{z}{w})^2)$$

for $-w/2 \le z \le w/2$ and

$p_{WB}(z) = 0$ elsewhere

Load between work roll and material:

$$p_{WSt}(z) = \frac{F_R}{w}$$

for $-w/2 \le z \le w/2$ and

$p_{WSt}(z) = 0$ elsewhere

### Internal values

| | |
|---|---|
| $z$ | Width variable [in. -> mm] |
| $p_{WB}$ | Load between work roll and backup roll [lb/in. -> N/mm] |
| $p_{WSt}$ | Load between work roll and strip [lb/in. -> N/mm] |

### Calculation Sequence

The calculation is done straight forward. For the calculation the work roll is divided into segments.

### References

none

# 4.11 Roll Deflection Model

### Description

The roll deflection model is used to calculate the mill stretch and the related mill modulus due to the deformation of the roll set in comparison of the cases "rolling" and "gauging". For this reason the deformation of the roll set is considered for these two cases:

- Material is within the roll gap (rolling)
- Work rolls are pressed against each other without material (gauging)

These cases are required because the measured mill stretch curve and the zero point of the roll adjustment which are the basis for the mill gauge model includes the deformation of the roll set with kissing work rolls.

The deflection calculation of the roll set deformation takes following effects into consideration:

- Roll deflection due to bending moment
- Roll
- deflection due to shear force
- Cross contraction due to bending moment
- Roll flattening

It is assumed that the pressure distribution between the work roll and the material is constant across the strip width and between the work and backup roll is parabolic.

### Input values

Pass data

$w$ Strip width [in. -> mm]

$F_R$ Rolling force [lb -> N]

$\Delta h$ Pass reduction [in. -> mm]

Backup roll data

$D_B$ Backup roll diameter [in. -> mm]

$D_{BN}$ Neck diameter of backup roll [in. -> mm]

$L_{BDB}$ Distance of bearing center of backup roll [in. -> mm]

$\Delta R_B$ Total roll crown of backup roll [in. -> mm]

$\Delta R_{B0}$ Basic roll crown (grinding) of backup roll [in. -> mm]

$E_B$ YOUNG's modulus backup roll [psi -> N/mm$^2$]

Work roll data

$D_W$ Work roll diameter [in. -> mm]

$\Delta R_W$ Total roll crown of work roll [in. -> mm]

$\Delta R_{W0}$ Basic roll crown (grinding) of work roll [in. -> mm]

$\Delta R_{WTherm}$ Thermal roll crown of work roll [in. -> mm]

$\Delta R_{WWear}$ Roll wear of work roll [in. -> mm]

$E_W$ YOUNG's modulus work roll [psi -> N/mm$^2$]

Common roll data

$\nu$ Average POISSON's ratio backup and work roll [1]

$L_B$ Barrel length of backup and work roll [in. -> mm]

**Output values**

$\delta_{RS}$ Mill stretch due to deformation of roll set [mm -> in.]

$C_{RS}$ Mill modulus due to deformation of roll set [N/mm -> lb/in.]

$c_{St}$ Strip profile [mm -> in.]

**Model equations:**

Deformation including displacement of work roll surface with material in roll gap:

$$\delta_W(z)\cdot\frac{\pi\cdot E_B\cdot L_B}{F_R}=H_V+1.1\cdot 10^{-5}\cdot\frac{\pi\cdot E_B\cdot L_B}{F_R}\cdot(D_B+D_W)-$$
$$(r_B+2\cdot r_W)\cdot(1-4\cdot z_L)+$$
$$\frac{2\cdot e\cdot(1-\nu^2)}{b}\cdot(\ln\frac{D_W}{l_d}-H_{XI})$$

for $-w/2\leq z\leq w/2$

Deformation including displacement of work roll surface without material (gauging):

$$\delta_{W0}(z)\cdot\frac{\pi\cdot E_B\cdot L_B}{F_R}=H_V+1.1\cdot 10^{-5}\cdot\frac{\pi\cdot E_B\cdot L_B}{F_R}\cdot(D_B+D_W)-(r_B+2\cdot r_W)\cdot(1-4\cdot z_L)+$$
$$e\cdot(1-\nu^2)\cdot(\ln\frac{D_W}{D_B}+$$
$$\ln\frac{D_B+D_W}{2F_R(1-\nu^2)\cdot(1/E_B+1/E_W)/(\pi\cdot L_B)}+0,3862)$$

for $-L_B/2\leq z\leq L_B/2$

and with $w=L_B$ in the below given definitions and abbreviations

Strip crown:

$$c_{St}=2\cdot(\delta_W(z=0)-\delta_W(z=w/2))$$

Mill stretch due to roll set (Difference Displacement of work rolls between empty roll gap and material in roll gap):

$$\delta_{RS}=2\cdot(\delta_W(z=0)-\delta_{W0}(z=0))$$

Mill modulus due to roll set (Differential quotient for displacement of work rolls):

$$1/C_{RS}=\frac{\partial\delta_{RS}(F_R)}{\partial F_R}=\frac{\delta_{RS}(F_R+\Delta F_R)-\delta_{RS}(F_R)}{\Delta F_R}$$

Following definitions are used:

$$C_q=1+\frac{H_I}{H_{III}}$$

$$H_I=H_{II}+(\frac{1}{d_B^4}+\frac{e}{d_w^4})(7-12a)-(\frac{1}{d_B^2}+\frac{e}{d_w^2})\frac{7+6\,\nu-2\,\nu^2}{1+\nu}$$

$$H_{II}=6(r_B+r_w)+e\frac{15+3\,\nu-36\,\nu^2}{4b(1+\nu)}+\frac{e(2-b)(7+6\,\nu-2\,\nu^2)}{d_w^2(1+\nu)}+$$

$$(\frac{e}{d_w^4})(b^3-4b^2+12a-4)$$

$$H_{III}=18(1-\nu^2)H_{IV}+2,2(\frac{1}{d_B^4}+\frac{e}{d_w^4})+(\frac{1}{d_B^2}+\frac{e}{d_w^2})\frac{7+6\,\nu-2\,\nu^2}{2(1+\nu)}+$$

$$(1+e)\frac{15+3\,\nu-36\,\nu^2}{8(1+\nu)}$$

$$H_{IV}=(1-e)\ln(\frac{d_B}{d_w})+9,8862(1+e)$$

$$H_V=H_{VI}\,/\,(30\cdot d_B^4)+H_{VII}\,/\,d_B^2+H_{VIII}\;+(1-\nu^2)\cdot H_{IX}\cdot H_X$$

$$H_{VI}=64\cdot(1-C_q)\cdot z_B^6+80\cdot C_q\cdot z_B^4-60\cdot(C_q+4\cdot a-3)\cdot z_B^2+C_q\cdot(16\cdot a-5)+$$
$$120\cdot a^2-156\cdot a+50+40\cdot d_{BN}^4\cdot(a-1)^3$$

$$H_{VII}=\frac{7+6\cdot\nu-2\cdot\nu^2}{3\cdot(1+\nu)}(4\cdot(C_q-1)\cdot z_B^4-2\cdot C_q\cdot z_B^2+\frac{1}{4}\cdot C_q)+$$
$$\frac{1}{4}\cdot(5+10\cdot\nu-\frac{\nu}{1+\nu})+$$
$$(\frac{2}{3}+\frac{4}{3}\cdot\nu-\frac{\nu}{1+\nu})\cdot a+(3+2\cdot\nu)\cdot d_{BN}^2\cdot(a-1)$$

$$H_{VIII}=\frac{5+\nu-12\cdot\nu^2}{48(1+\nu)}(C_q-12\cdot(C_q-1)\cdot z_B^2)$$

$$H_{IX}=(1-e)\cdot\ln(d_B\,/\,d_W)+9.8862\cdot(1+e)$$

$$H_X = C_q - 12 \cdot (C_q - 1) \cdot z_B^2$$

$$H_{XI} = 0 \text{ for } -(b - d_W) \le 2 \cdot z_B \le (b - d_W)$$

$$H_{XI} = 0{,}95 \cdot (2z_B / d_W - b / d_W + 1)^{10/3} \text{ für } b - d_W \le 2z_B \le b \text{ and } b - d_W \le 2z_B \le b$$

$$l_d = \sqrt{\Delta h \cdot D_W / 2}$$

Following abbreviations are used

$$a = L_{BDB} / L_B$$
$$b = w / L_B$$
$$e = E_B / E_W$$
$$d_B = D_B / L_B$$
$$d_W = D_W / L_W$$
$$r_B(z) = \Delta R_B(z) \cdot \frac{\pi \cdot E_B \cdot L_B}{F_R}$$
$$r_W(z) = \Delta R_W(z) \cdot \frac{\pi \cdot E_B \cdot L_B}{F_R}$$
$$z_L = z / L_B$$
$$d_{BN} = D_B / D_{BN}$$

Total work roll crown:

$$\Delta R_W = \Delta R_{W0} + \Delta R_{WTherm} + \Delta R_{RWear}$$

Total backup roll crown:

$$\Delta R_B = \Delta R_{B0}$$

### Internal values

$z$ Width variable in direction of roll axis [in. -> mm]
z=0 center of roll set
z=w/2 strip edge

$\Delta F_R$ Roll force increment [lb -> N]

### Calculation sequence

The calculation is done straight forward for each stand and for each strip for the strip head end.

### References

[1] B.Berger, Dissertation "Die elastische Verformung der Walzen von Quarto-Walzgerüsten, 1975

## 4.12 Thermal Work Roll Model

### Description

By the aid of the thermal work roll model the expansion and contraction of the work roll due to the rise and drop of work roll temperature during rolling and gap times between rolling is calculated. The model considers effects as:

- Temperature rise due to the heat flow from the material into the work roll
- Temperature drop due to the heat flow from the work roll to the coolant of the roll cooling system
- Temperature drop due to the heat flow from the work roll to the surroundings

The calculation is done by the aid of a differential method based on heat balance considerations.

### Input values

Pass data

$w$ Strip width [in. -> m]

$T_{st}$ Strip temperature [°F -> K]

$t_p$ Pass time [s]

$t_0$ Time to next material [s]

Work roll data

$R_W$ Roll radius [in. -> m]

$R_{WN}$ Roll neck radius [in. -> m]

$L_B$ Barrel length [in. -> m]

$L_W$ Roll length [in. -> m]

$\rho$ Density [lb/in.³ -> kg/m³]

$c$ Specific heat capacity [Btu/lb/°F -> J/kg/K]

$\lambda$ Thermal conductivity [Btu·in./s/ft²/°F -> W/m/K]

$\gamma$ Thermal expansion coefficient [1/°F -> 1/K]

Cooling and heating data

$\alpha_E$ Heat transfer coefficient roll to air [Btu/ft²/h/°F -> W/m²/K]

$\alpha_c$ Heat transfer coefficient roll to coolant [Btu/ft²/h/°F -> W/m²/K]

$\varphi_c$ Total cooling angle per work roll [deg]

$T_w$ Coolant temperature [°F -> K]

$T_0$ Ambient temperature (initial work roll temperature) [°F -> K]

$k_{eff}$ Coefficient heat flow from strip to work roll [Btu/ft²/h/°F -> W/m²/K]

Adapters

$k_H$ Adapter heat flow from strip to roll [1]

$k_c$ Adapter heat flow from work roll to coolant [1]

**Output values**

$\Delta R_{wTherm}$ Thermal work roll crown [m -> in.]

$c_{st}$ Thermal strip crown [m -> in.]

$a_0$ Thermal work roll crown coefficient [m -> in.]

$a_1$ Thermal work roll crown coefficient [1/s]

**Model equations:**

Increment of work roll temperature for the i-th Element:

$$\Delta T_i = \frac{\partial T_i}{\partial t} \cdot \Delta t + \frac{\partial^2 T_i}{\partial t^2} \cdot \Delta t^2 / 2$$

for $i = 1, \ldots, N$

i is 1 for the middle of the work roll and i is N for the right end of the work roll. z-coordinate in the direction of work roll axis:

$$z = \frac{i}{2} \cdot \Delta z$$

Updated work roll temperature for i-th element :

$$T_{i+1} = T_i + \Delta T_i$$

First derivation of work roll temperature:

$$\frac{\partial T_i}{\partial t} = \theta_1 \cdot \frac{2 \cdot k_{eff}}{R \cdot \rho \cdot c} \cdot (T_{st} - T_i) - \theta_2 \cdot \frac{2 \cdot \alpha_{Ceff}}{R \cdot \rho \cdot c} \cdot (T_i - T_W) - \theta_3 \cdot \frac{2 \cdot \alpha_E}{R \cdot \rho \cdot c} \cdot (T_i - T_0) +$$
$$\theta_4 \cdot \frac{\lambda}{\rho \cdot c \cdot \Delta z^2} \cdot (T_{i+1} - T_i) - \theta_5 \cdot \frac{\lambda}{\rho \cdot c \cdot \Delta z^2} \cdot (T_i - T_{i-1}) -$$
$$\theta_6 \cdot \frac{(R_B^2 - R_N^2) \cdot \alpha_E}{R_B^2 \cdot \rho \cdot c} \cdot (T_i - T_0) - \theta_7 \cdot \frac{\alpha_E}{\Delta z \cdot \rho \cdot c} \cdot (T_i - T_0)$$

Second derivation of work roll temperature:

$$\frac{\partial^2 T_i}{\partial t^2} = (-\theta_1 \cdot \frac{2 \cdot k_{eff}}{R \cdot \rho \cdot c} - \theta_2 \cdot \frac{2 \cdot \alpha_{Ceff}}{R \cdot \rho \cdot c} - \theta_3 \cdot \frac{2 \cdot \alpha_E}{R \cdot \rho \cdot c} -$$
$$\theta_4 \cdot \frac{\lambda}{\rho \cdot c \cdot \Delta z^2} - \theta_5 \cdot \frac{\lambda}{\rho \cdot c \cdot \Delta z^2} -$$
$$\theta_6 \cdot \frac{(R_W^2 - R_{WN}^2) \cdot \alpha_E}{R_W^2 \cdot \rho \cdot c} - \theta_7 \cdot \frac{\alpha_E}{\Delta z \cdot \rho \cdot c}) \frac{\partial T_i}{\partial t}$$

Heat flow from strip to work roll. For adaptation reasons the coefficient is represented as follows

$$k_{eff} = k_{eff}^{*} \cdot k_H$$

$k_{eff}^{*}$ is calculated as defined in roll gap temperature model.

Heat flow from work roll to coolant of the cooling system. For adaptation reasons the coefficient is represented as follows

$$\alpha_{Ceff} = \frac{\varphi_C}{360} \cdot \alpha_c^{*} \cdot k_C$$

Definition of switch variables::

$\theta_1 = \theta_{1st} \cdot \theta_{1z}$

$\theta_{1st}$ 1 if strip is in roll gap

0 if roll gap is empty

$\theta_{1z}$ 1 if $z \le w/2$

0 if $z > w/2$

$\theta_2$ 1 if cooling system is on

0 if cooling system is off

$\theta_3 = 1 - \theta_2$

$\theta_4$ 1 for i < N

0 for i = N

$\theta_5$ 1 for i > N

0 for i = 0

$\theta_6 = 1 \text{ for } z = L_B/2$

$= 0 \text{ for } z \ne L_B/2$

$\theta_7 = 1 - \theta_4$

Definition of work roll radius:

$$
\begin{aligned}
R &= R_W \text{ for } z \le L_B / 2 \\
&= R_{BN} \text{ for } z > L_B / 2
\end{aligned}
$$

Thermal work roll crown:

$$c(z) = R_W \cdot \gamma \cdot (T(z) - T_0)$$

Thermal strip crown

$$c_{st} = R_W \cdot \gamma \cdot (T(z=0) - T(z = w/2))$$

Average work roll radius change:

$$\Delta R_{wTherm} = \frac{\Delta z \cdot R_W \cdot \gamma}{L_B} \sum_i (T_i - T_0)$$

Approximation of change of work roll radius

$$\Delta R_{WTherm}(t) = a_0 \cdot e^{a_1 \cdot t}$$

### Internal values

$z$ Width variable in direction of roll axis [in. -> m]
z=0 center of roll set
z=w/2 strip edge

$z = L_B / 2$ Roll barrel edge

$z = L_W / 2$ Roll edge

$T_i$ Temperature of i-th work roll element [°F -> °C]

$\Delta t$ Time increment [s]

$\Delta z$ Roll width increment [in. -> m]

### Calculation sequence

The calculation is done by iteration over time and width:

$$
\begin{aligned}
&\text{for } (t = t_0, T(z,t) = T_0(z); t \le t_{tot}; t = t + \Delta t) \\
&\quad \text{for } (z = 0; z < L_B / 2; z = z + \Delta z) \\
&\qquad \Delta T(z, t + \Delta t) = \Delta T(T(z,t), z, \Delta t) \\
&\qquad T(z, t + \Delta t) = T(z,t) + \Delta T(z, t + \Delta t)
\end{aligned}
$$

**References**

none

## 4.13 Mass Flow Considerations

### Description

With the aid of the mass flow considerations the speeds, locations and times of strip segments can be calculated for a given plant location. This submodel is an integral part of the rolling strategy.

### Input values

| | |
|---|---|
| $h_i$ | Thickness [in. -> m] |
| $f_{v,Fi}$ | Forward slip [1] |
| $v_{R,F6}$ | Rolling speed stand F6 [ft/min -> m/s] |
| $L_x$ | Strip segment location related to final strip [ft -> m] |
| $t_{F1,0}$ | Time when strip head enters stand F1 [s] |
| $w_i$ | Width [in -> mm] |
| $\Delta p_{Fi}$ | Distance between stands [ft -> m] |
| $\Delta p_{AR-F1}$ | Distance between position at approach roller table and stand F1 [ft -> m] |

### Output values

| | |
|---|---|
| $v_{EX,Fi}$ | Stand exit speeds [m/s -> ft/min] |
| $v_{EN,Fi}$ | Stand entry speed [m/s -> ft/min] |
| $t_{Fi}$ | Time when strip segment enters stand Fi [s] |
| $t_{RO,p}$ | Time when strip segment reaches a certain position at the run-out table [s] |
| $t_{AR,p}$ | Time when strip segment reaches a certain position at the run-out table [s] |

### Submodels

none

### Model equations

Stand exit strip speed:

$$v_{EX,Fi} = v_{R,F6} \cdot f_{v,F6} \cdot \frac{h_6 \cdot w_6}{h_i \cdot w_i}$$

Stand rolling strip speed:

$$v_{R,Fi} = v_{R,F6} \cdot \frac{h_6 \cdot w_6 \cdot f_{v,F6}}{h_i \cdot w_i \cdot f_{v,Fi}}$$

Time when strip segment enters stand Fi:

$$t_{Fi} = t_{F1,0} + \frac{1}{v_{R,F6} \cdot f_{v,F6}} (L_x + \sum_{j=1}^{i-1} \frac{h_i \cdot \Delta p_{Fi}}{h_6})$$

Time when strip segment reaches a certain position at the run-out table:

$$t_{RO,p} = t_{F1,0} + \frac{1}{v_{R,F6} \cdot f_{v,F6}} (L_x + \sum_{j=1}^{5} \frac{h_i \cdot \Delta p_{Fi}}{h_6} + p_{F6-RO})$$

Time when strip segment reaches a certain position at the approach roller table:

$$t_{AR,p} = t_{F1,0} - \frac{L_x \cdot h_6}{v_A \cdot h_0} \quad \text{for } L_x < \Delta p_{AR-F1} \cdot \frac{h_0}{h_6}$$

$$t_{AR,p} = t_{F1,0} - \frac{L_x \cdot h_6}{v_A \cdot h_0} - \frac{L_x - \Delta p_{AR-F1} \cdot \frac{h_0}{h_6}}{v_{R,F6} \cdot f_{v,F6}} \quad \text{for } L_x > \Delta p_{AR-F1} \cdot \frac{h_0}{h_6}$$

### Internal values

none

### Calculation sequence

The calculation is done straight forward and described above.

### References

none

## 4.14 Calculation of Transfer Bar Thickness

### Description

The transfer bar thickness will be calculated by the actual roll force and screw down position of the rougher.

### Input values

| | |
|---|---|
| $s_{RM,x}$ | Screw down position rougher [in. -> mm] |
| $F_{RM,x}$ | Roll force rougher [lb -> kN] |
| $s_{RM,0}$ | Calibration screw down position rougher [in. -> mm] |
| $F_{RM,0}$ | Calibration roll force rougher [lb -> kN] |
| $C_{RM,tot}$ | Mill stretch rougher [lb/in. -> kN/mm] |
| $\delta_{RM,corr}$ | Correction transfer bar thickness [in. -> mm] |

### Output values

| | |
|---|---|
| $h_{TB,head}$ | Transfer bar thickness head [mm -> in.] |

### Submodels

none

### Model equations

Transfer bar thickness:

$$h_{TB,x} = (s_{RM,x} - s_{RM,0}) + \frac{F_{RM,x} - F_{RM,0}}{C_{RM,tot}} + \delta_{RM,corr}$$

### Internal values

$h_{TB,x}$ Transfer bar thickness [in. -> mm]

### Calculation sequence

The calculation is done straight forward and described above.

### References

none

# 5. Model adaptation

## 5.1 Temperature Adaptation

### Description

The temperature adaptation is used to correct the error on the finishing temperature between the prediction and the measurement. For this reason a general muliplicator is used. The difference between the predicted and the actual measured temperature is evaluated and will be considered for the succeeding strips of the same steel grade.

### Input values

$L_{h_i,x}$ Strip segment [ft -> m]

$T^*_{R,x}$ Measured roughing stand temperature [°F -> °C]

$T^*_{F,x}$ Measured finishing exit temperature [°F -> °C]

$T_{HC\_tail\_last\_strip}$ Heat cover temperature after tail last strip [°F -> °C]

$\Delta t_{HC\_head\_to\_tail}$ Time tail to head [s]

$k_{tot}$ Adapter for temperature effects [1]

$g$ Learning rate [%]

### Output values

$k_{new}$ New adapter for temperature effects.[1]

### Submodels

$T_{RG}$ Roll gap temperature model

$T_{RAD}$ Radiation temperature model

$T_{WC}$ Descaling and interstand cooling model

$T_{HCSt}$ Heat cover strip temperature model

Strip segment tracking

**Model equations**

Consideration of a certain strip segment:

$$L_{h_i,x} = L_{h_i}(L_{h_6,x})$$

Transfer bar temperature at rouging stand:

$$T^*_{R,x} = T^*_R(L_{h_0,x}, z) \quad \text{with } \frac{\partial T_R}{\partial z} = 0$$

Transfer bar temperature at the entry of the heat cover:

$$T_{HCEN,x} = T_{HCEN}(L_{h_0,x}) = T_{RAD}(T^*_{R,x}, \Delta t_{TR-HCEN,x}, k_{tot} \cdot \varepsilon)$$

Heat cover temperature when strip head enters the heat cover:

$$T_{HC,0} = T_{HC}(L_{h_0,x} = 0) = T_{HC\_no\_strip}(T_{HC\_tail\_last\_strip}, \Delta t_{HC\_head\_to\_tail})$$

Heat cover temperature when strip segment enters the heat cover:

$$T_{HC,x} = T_{HC}(L_{h_0,x}) = T_{HC\_with\_strip}(T_{HC,0}, \Delta t_{HC\_heat,x}, k_{tot} \cdot \varepsilon)$$

Transfer bar temperature at the exit of the heat cover:

$$T_{HCEX,x} = T_{HCEX}(L_{h_0,x}) = T_{HCSt}(T_{HCEN,x}, T_{HC,x}, \Delta t_{HC,x}, k_{tot} \cdot \varepsilon)$$

Transfer bar temperature before descaler:

$$T_{DESEN,x} = T_{DESEN}(L_{h_0,x}) = T_{RAD}(T_{HCEX,x}, \Delta t_{HCEX-DES,x}, k_{tot} \cdot \varepsilon)$$

Transfer bar temperature after descaler:

$$T_{DESEX,x} = T_{DESEX}(L_{h_0,x}) = T_{WC}(T_{DESEN,x}, \Delta t_{DES,x}, k_{tot} \cdot \alpha)$$

Transfer bar temperature before finishing stand F1:

$$T_{F1EN,x} = T_{F1EN}(L_{h_0,x}) = T_{RAD}(T_{DESEX,x}, \Delta t_{DES-F1,x}, k_{tot} \cdot \varepsilon)$$

Strip temperature after a certain finishing stand:

$$T_{FiEX,x} = T_{FiEX}(L_{h_i,x}) = T_{RG}(T_{FiEN,x}, k_{tot})$$

Strip temperature before a certain finishing stand with interstand cooling:

$$T_{FiEN,x} = T_{FiEN}(L_{h_i,x}) = T_{WC}(T_{F(i-1)EX,x}, \Delta t_{F(i-1)EX-FiEN,x}, k_{tot} \cdot \alpha)$$

Strip temperature before a certain finishing stand without interstand cooling:

$$T_{FiEN,x} = T_{FiEN}(L_{h_i,x}) = T_{RAD}(T_{F(i-1)EX,x}, \Delta t_{F(i-1)EX-FiEN,x}, k_{tot} \cdot \varepsilon)$$

Strip temperature at finishing temperature measuring device:

$$T_{F,x} = T_F(L_{h_6,x}) = T_{RAD}(T_{F6,x}, \Delta t_{F6EX-FT,x}, k_{tot} \cdot \varepsilon)$$

Measured temperature drop

$$\Delta T_x^* = T_{R,x}^* - T_{F,x}^*$$

Calculated temperature drop

$$\Delta T_x = T_{R,x}^* - T_{F,x}$$

Calculation of the temperature adapter

$$k_{tot} = \frac{\sum \Delta T_x^*}{\sum \Delta T_x} \cdot k_{tot,old}$$

Inheritance of adapters:

$$k_{tot,new} = (1 - \frac{g}{100}) \cdot k_{tot,old} + \frac{g}{100} \cdot k_{tot}$$

**Internal values**

$z$ Coordinate in strip thickness direction [in. -> mm]

$\Delta t$ Transportation times [s]

**Calculation sequence**

The calculation is done straight forward.

**References**

none

## 5.2 Thickness Adaptation

### Description

The thickness adaptation is used to calculate a correction term of the gauge meter model due to the measurement of the thickness gauge after the finishing mill.

The range of measurements affecting the thickness adaptation is limited to the headend to avoid overlay with the in-strip corrections done by the AGC thickness monitor control loop.

### Input values

| | |
|---|---|
| $h^{*}_{xray,j}$ | Measured finished strip thickness [in. -> mm] |
| $h_{tgt,cold}$ | Target strip thickness,cold [in. -> mm] |
| $\delta_{corr,old}$ | New thickness adapter [in. -> mm] |
| $g$ | Learning rate [%] |

### Output values

| | |
|---|---|
| $\delta_{corr,new}$ | New thickness adapter [mm -> in.] |

### Submodels

None

### Model equation

Calculation of average thickness adapter:

$$\overline{\delta_{corr}} = \left( \frac{1}{J} \sum_{j=1}^{J} h^{*}_{xray,j} \right) - h_{tgt,cold}$$

Inheritance of thickness adapter:

$$\delta_{corr,new} = (1 - \frac{g}{100}) \cdot \delta_{corr,old} + \frac{g}{100} \cdot \overline{\delta_{corr}}$$

### Internal values

$\delta_{corr,x}$ Thickness adapter for strip segment [in. -> mm]

$\overline{\delta_{corr}}$ Thickness adapter for strip [in. -> mm]

### Calculation Sequence

The calculation is done straight forward.

### References

none

## 5.3 Stand Speed Adaptation

### Description

Deviations of the calculated and the required stand speeds are mainly a result of deviations in the loadgaps and the strip dimensions. After threading and ramping down the leadspeed (the level 1 precompensation for speed drop caused by the drive load change on impact), the maindrive-looper control adjusts the stand speeds using a supplimentary speed which is added to the setpoint reference speed. To preadjust the setpoint reference speed as exactly as possible to the requirements, the model uses stand speed adapters which are derived from the actual stand speeds in the intervall from the time after the leadspeed is ramped down to the end of the strip.

### Input values

| | | |
|---|---|---|
| $v^*_{stno,j}$ | Measured stand speed | [fpm] |
| $v^*_{stno}$ | Average of measured stand speed | [fpm] |
| $v_{stno}$ | Stand speed setpoint | [fpm] |
| $cor_{old,stno}$ | Old speed adapter | [%] |
| g | Learning rate | [%] |

### Output values

| | | |
|---|---|---|
| $cor_{new,stno}$ | New speed adapter | [%] |

### Submodels

None

### Model equation

Calculation of average stand speed

$$v^*_{stno} = \frac{1}{J}\sum_{j=1}^{J} v^*_{stno,j}$$

Calculation of the pure deviations

$$dev_{pure,stno} = \frac{v^*_{stno} - v_{uncor,stno}}{v_{uncor,stno}} \cdot 100$$

To avoid a slow-down of the whole mill by the speed adaptation, the speed adapters are centered along the zero line.

$$dev_{center} = \frac{1}{s\tan ds} \sum_{j=fists\tan d}^{lasts\tan d} dev_{pure,stno}$$

Inheritance of thickness adapter:

$$cor_{new,stno} = co\ r_{old,stno} + \frac{g}{100} \cdot \left( dev_{pure} - dev_{center} \right)$$

**Internal values**

$dev_{pure,stno}$ Deviation of actual speed to setpoint speed [%]

$dev_{center}$ Deviation of stand deviations from zero line [%]

**Calculation Sequence**

The calculation is done straight forward.

**References**

none

## 5.4 Adaptation of Material Equation

### Description

The adaptive coefficients of the material equation are updated with each new available measurement record. For this reason the 'roll force and torque model' in combination with the 'material equation' is linearized. This is done by a recursive weighted least squares technique that is due to YOUNG. A numerically stable square root implementation of this algorithm is used.

### Input values

Measured (or derived) data

| | |
|---|---|
| $w_i^{mea}$ | Width [in. -> mm] |
| $F_i^{mea}$ | Roll force [lb -> kN] |
| $TOR_i^{mea}$ | Roll torque [lb·ft -> kNm] |
| $h_{1,i}^{mea}$ | Entry thickness [in. -> mm] |
| $h_{2,i}^{mea}$ | Exit thickness [in. -> mm] |
| $T_i^{mea}$ | Entry temperature [°F -> °C] |
| $v_{w,i}^{mea}$ | Rolling speed [ft./min -> m/s] |
| $stno_i$ | Stand number indication [1] |

Stand data

| | |
|---|---|
| $r_{i_{stno}}$ | Work roll radius [in. -> mm] |
| $E_{i_{stno}}$ | YOUNG's modulus [psi -> N/mm²] |
| $\nu_{i_{stno}}$ | POISSON's ratio [1] |

Adaptation data

| | |
|---|---|
| $k_{f0}^{old}$ | Old general coefficient [1] |

$m_1^{old}$ Old temperature coefficient [1]

$m_2^{old}$ Old speed coefficient [1]

$m_3^{old}$ Old strain coefficient [1]

$m_{4,i_{stno}}^{old}$ Old recrystallization coefficient [1]

$\eta^{old}$ Old torque coefficient [1]

$S_{old}^F$ Old propagation matrix for roll force [1]

$S_{old}^T$ Old propagation value for roll torque [1]

$\varepsilon_{\lim}^F$ Residual limitation for force [ln(psi) -> ln(N/mm²)]

$\varepsilon_{\lim}^T$ Residual limitation for torque [lb·ft -> kNm]

$g_{m_4}$ Learning rate for recrystallization coefficient [%]

$g$ Exp. memory constant for recursive adaptation [1]

General data

$i_{sgcl}$ Steel grade class [1]

**Output values**

$k_{f0}^{new}$ New general coefficient [1]

$m_1^{new}$ New temperature coefficient [1]

$m_2^{new}$ New speed coefficient [1]

$m_3^{new}$ New strain coefficient [1]

$m_{4,i_{stno}}^{new}$ New recrystallization coefficient [1]

$\eta^{new}$ New torque coefficient [1]

$S_{new}^F$ New propagation matrix for roll force [1]

$S_{new}^T$ New propagation value for roll torque [1]

### Submodels

Roll force and torque model
Material equation
Roll gap temperature model
Radiation temperature model
Descaling and cooling model
Heat cover temperature model

### Model equations:

The roll force and torque model can be considered as linear equation $y = x' \cdot a$:

Roll force

$$F = \left(k_f^F \cdot ff - F_{tens}\right) \cdot 10^{-3}$$

$$\Downarrow \quad (m_4 := 1)$$

$$\ln\left(10^3 \cdot F + F_{tens}\right) - \ln(ff) = \ln\left(k_{f0}\right) + \left(-m_1\right) \cdot T + m_2 \cdot \ln(\dot{\varphi}) + m_3 \cdot \ln\left(\varphi_{tot}\right)$$

$$\Downarrow$$

$$\underbrace{\ln\left(10^3 \cdot F + F_{tens}\right) - \ln(ff)}_{y} = \underbrace{\left[1 \quad T \quad \ln(\dot{\varphi}) \quad \varphi_{tot}\right]}_{x'} \cdot \underbrace{\begin{bmatrix} \ln\left(k_{f0}\right) \\ -m_1 \\ m_2 \\ m_3 \end{bmatrix}}_{a}$$

Roll torque

$$TOR = \left(k_f^T \cdot tt + TOR_{tens}\right) \cdot 10^{-6}$$

$$\Downarrow$$

$$\underbrace{10^6 \cdot TOR - TOR_{tens}}_{y} = \underbrace{\left(k_f^F \cdot tt\right)}_{x'} \cdot \underbrace{\eta}_{a}$$

Assuming that n records with measured data are available we can establish the following matrices and vectors:

Roll force

$$y=\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}=\begin{bmatrix} \left\langle \ln\left(10^3 \cdot F + F_{tens}\right) - \ln\left(ff\right)\right\rangle_1^{mea} \\ \left\langle \ln\left(10^3 \cdot F + F_{tens}\right) - \ln\left(ff\right)\right\rangle_2^{mea} \\ \vdots \\ \left\langle \ln\left(10^3 \cdot F + F_{tens}\right) - \ln\left(ff\right)\right\rangle_n^{mea} \end{bmatrix}$$

$$X=\begin{bmatrix} x'_1 \\ x'_2 \\ \vdots \\ x'_n \end{bmatrix}=\begin{bmatrix} 1 & \langle T\rangle_1^{mea} & \langle \ln(\dot{\varphi})\rangle_1^{mea} & \langle \varphi_{tot}\rangle_1^{mea} \\ 1 & \langle T\rangle_2^{mea} & \langle \ln(\dot{\varphi})\rangle_2^{mea} & \langle \varphi_{tot}\rangle_2^{mea} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \langle T\rangle_n^{mea} & \langle \ln(\dot{\varphi})\rangle_n^{mea} & \langle \varphi_{tot}\rangle_n^{mea} \end{bmatrix}$$

Roll torque

$$y=\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}=\begin{bmatrix} \left\langle 10^6 \cdot TOR - TOR_{tens}\right\rangle_1^{mea} \\ \left\langle 10^6 \cdot TOR - TOR_{tens}\right\rangle_2^{mea} \\ \vdots \\ \left\langle 10^6 \cdot TOR - TOR_{tens}\right\rangle_n^{mea} \end{bmatrix}$$

$$X=\begin{bmatrix} x'_1 \\ x'_1 \\ \vdots \\ x'_1 \end{bmatrix}=\begin{bmatrix} \left\langle k_f^F \cdot tt\right\rangle_1^{mea} \\ \left\langle k_f^F \cdot tt\right\rangle_2^{mea} \\ \vdots \\ \left\langle k_f^F \cdot tt\right\rangle_n^{mea} \end{bmatrix}$$

For the off-line identification of the models the parameter vector a will be determined in a way that:

$$\sum_{i=1}^{n}\left(y_i - x_i' \cdot a\right)^2 \xrightarrow[a]{} MIN \qquad \text{Least squares fit}$$

$$\Downarrow$$

$$X' \cdot X \cdot a = X' \cdot y \qquad \text{Normal equations}$$

$$\Downarrow$$

$$a = \left(X' \cdot X\right)^{-1} \cdot X' \cdot y$$

Then the parameters of the material equation (up to $m_4$) can be computed like this:

$$\begin{bmatrix} k_{f0} \\ m_1 \\ m_2 \\ m_3 \end{bmatrix} = \begin{bmatrix} e^{a_1} \\ -a_2 \\ a_3 \\ a_4 \end{bmatrix} \qquad \text{and} \qquad \eta = a$$

For the above regression analysis data from all stands are used. The parameter $m_4$ will be estimated separately for each stand using only the measured data of the individual stand. The other parameters of the material equation are considered constant:

$$\underbrace{10^3 \cdot F + F_{tens}}_{y} = \underbrace{ff \cdot k_{f0} \cdot e^{-m_1 \cdot T} \cdot \dot{\varphi}^{m_2} \cdot \varphi_{tot}^{m_3}}_{x'} \cdot \underbrace{m_{4,i_{stno}}}_{a}$$

$$m_{4,i_{stno}} = \frac{\sum_{i=1}^{n_{i_{stno}}} x_i \cdot y_i}{\sum_{i=1}^{n_{i_{stno}}} x_i^2} = \frac{\sum_{i=1}^{n_{i_{stno}}} \left\langle ff \cdot k_{f0} \cdot e^{-m_1 \cdot T} \cdot \dot{\varphi}^{m_2} \cdot \varphi_{tot}^{m_3} \right\rangle_i^{mea_{i_{stno}}} \cdot \left\langle 10^3 \cdot F + F_{tens} \right\rangle_i^{mea_{i_{stno}}}}{\sum_{i=1}^{n_{i_{stno}}} \left( \left\langle ff \cdot k_{f0} \cdot e^{-m_1 \cdot T} \cdot \dot{\varphi}^{m_2} \cdot \varphi_{tot}^{m_3} \right\rangle_i^{mea_{i_{stno}}} \right)^2}$$

$$i_{stno} = 1,2,\ldots,6 \qquad \text{Stand number index}$$

Then the parameters of the material equation for a certain steel grade class look like this:

$$\begin{bmatrix} & & k_{f0} & & & \\ & & m_1 & & & \\ & & m_2 & & & \\ & & m_3 & & & \\ m_{4,1} & m_{4,2} & m_{4,3} & m_{4,4} & m_{4,5} & m_{4,6} \\ & & \eta & & & \end{bmatrix} \begin{matrix} \text{General coefficient} \\ \text{Temperature coefficient} \\ \text{Speed coefficient} \\ \text{Strain coefficient} \\ \text{Recrystallization coefficients} \\ \text{Torque coefficent} \end{matrix}$$

For the purpose of <u>on-line adaptation</u> additionally square roots S of the inverse matrices $(X'.X)^{-1}$ [i.e. $S.S' = (X'.X)^{-1}$] obtained at the regression analysis have to be stored for the roll force and roll torque parameters. This matrices will be called 'propagation matrices' in the sequel:

$$\begin{bmatrix} k_{f0} \\ m_1 \\ m_2 \\ m_3 \end{bmatrix} \leftrightarrow \begin{bmatrix} s_{11}^F & s_{12}^F & s_{13}^F & s_{14}^F \\ s_{21}^F & s_{22}^F & s_{23}^F & s_{24}^F \\ s_{31}^F & s_{32}^F & s_{33}^F & s_{34}^F \\ s_{41}^F & s_{42}^F & s_{43}^F & s_{44}^F \end{bmatrix} \text{ and } \quad \eta \leftrightarrow s^T$$

The following recursive algorithm will be used for the adaptation of the material equation (up to $m_4$):

$$Q_{n+1} = S_n \cdot x_{n+1}$$

$$\gamma = \frac{1-g}{g}$$

$$\alpha_{n+1} = \frac{1}{Q'_{n+1} \cdot Q_{n+1} + \gamma}$$

$$\lambda_{n+1} = \frac{1}{1+\sqrt{\alpha \cdot \gamma}}$$

$$S_{n+1} = \frac{1}{\sqrt{1-g}} \cdot \left( S_n - \alpha_{n+1} \cdot \lambda_{n+1} \cdot S_n \cdot Q_{n+1} \cdot Q'_{n+1} \right)$$

$$\varepsilon_{n+1} = x'_{n+1} \cdot a_n - y_{n+1}$$

$$\varepsilon'_{n+1} = \min\left(\max\left(\varepsilon, -\varepsilon_{\lim}\right), +\varepsilon_{\lim}\right)$$

$$a_{n+1} = a_n - g \cdot S_{n+1} \cdot S'_{n+1} \cdot x_{n+1} \cdot \varepsilon'_{n+1}$$

where

| | |
|---|---|
| $a_n$ | old parameter vector |
| $a_{n+1}$ | new parameter vector |
| $S_n$ | old propagation matrix |
| $S_{n+1}$ | new propagation matrix |
| $(x_{n+1}, y_{n+1})$ | new observation (measurement) |
| $0 < g \leq 0.1$ | exp. memory constant $(g \downarrow$ long $g \uparrow$ short memory$)$ |
| $\varepsilon_{\lim} > 0$ | residual limitation (outlier control) |

The adaptation of the recrystallization coefficients is performed as follows

$$m_{4,n+1} = \left(1 - \frac{g_{m_4}}{100}\right) \cdot m_{4,n} + \frac{g_{m_4}}{100} \cdot m_{4,rec}$$

where

| | |
|---|---|
| $g_{m_4}$ | Learning rate $[\%]$ |
| $m_{4,rec}$ | Recalculated coefficient (as described above) |

### Internal values

none

### Calculation sequence

The calculation is done straight forward.

### References

[1] P.C. YOUNG: Applying parameter estimation to dynamic systems - part 1, Control Engineering (1969) 119-125.

[2] P.G. KAMINSKI et al: Discrete square root filtering: A survey of current techniques, IEEE Transactions on Automatic Control (1971) 727-736.

[3] M. MATTILA, P. MÄNTYALÄ: On-line parameter estimation in pass scheduling for plate rolling.

[4] A.F. MacALISTER: Modelling and adaptive techniques for rolling mill automation, Iron and Steel Engineer (1989) 38-46.

## 5.5 Strip Segment Tracking

### Description

The strip segment tracking allows to determine the time and location of a strip segment within the considered mill area on their way through the plant. This is especially relevant for the temperature calculations. The strip segments are related to the final strip.

### Input values

| | |
|---|---|
| $L_{h_6,x}$ | Strip segment related to final strip [ft -> m] |
| $\Delta L_{h_i,j}$ | Measured strip locations [ft -> m] |
| $\Delta t_{h_i,j}$ | Measured time intervals related to the event strip enters stand [s] |
| $t_{Fi,0}$ | Time when strip enters a certain finishing stand Fi [s] |
| $t_{R,0}$ | Time when transfer bar enters rouging stand R [s] |
| $v_{h_i,j}$ | Measured rolling speed [ft/min -> m/s] |
| $f_{v,h_i}$ | Forward slip [1] |
| $p$ | Distance of plant location to a stand [ft -> m] |

### Output values

| | |
|---|---|
| $L_{h_i,x}$ | Strip segment related to a certain intermediate thickness (stand) [m -> ft] |
| $t_{Fi,x}$ | Time when a certain strip segment leaves a finishing stand [s] |
| $t_{R,x}$ | Time when a certain strip segment leaves the roughing stand [s] |
| $t_{Fi,x,p}$ | Time when a certain strip segment passes a certain plant location behind a finishing stand [s] |
| $t_{R,x,p}$ | Time when a certain strip segment passes a certain plant location behind the roughing stand [s] |

**Model equations:**

Transformation of a given strip segment $L_{h_6,x}$ related to the exit of stand F6 to a certain strip thickness $L_{h_i,x}$:

$$L_{h_{i,x}} = L_{h_i}(L_{h_6,x})$$

with the relations

$$L_{h_6,x} = \sum_{k=1}^{K-1} \Delta L_{h_6,k}$$

$$L_{h_i,x} = \sum_{j=1}^{J-1} f_{h_i} \cdot \Delta L_{h_i,j} + f_{h_i} \cdot \delta L_{h_i}$$

$$\sum_{k=1}^{K-1} \Delta L_{h_6,k} \cdot h_{6,k} = \sum_{j=1}^{J-1} f_{h_i} \cdot \Delta L_{h_i,j} \cdot h_{i,j} + f_{h_i} \cdot \delta L_{h_i} \cdot h_{i,J}$$

$$\sum_{k=1}^{K_{tot}-1} \Delta L_{h_6,k} \cdot h_{6,k} = \sum_{j=1}^{J_{tot}-1} f_{h_i} \cdot \Delta L_{h_i,j} \cdot h_{i,j}$$

Time when strip segment $L_{h_6,x}$ leaves finishing stand F6:

$$t_{F6,x} = t_{F6,0} + \sum_{k=1}^{K-1} \Delta t_{F6,k}$$

Time when strip segment $L_{h_i,x}$ leaves finishing stand Fi:

$$t_{Fi,x} = t_{Fi,0} + \sum_{j=1}^{J-1} \Delta t_{Fi,j} + \frac{\delta L_{h_i}}{f_{v,h_i} \cdot v_{h_i,J}}$$

Time when strip segment $L_{h_i,x,p}$ passes a certain position p between finishing stand Fi and next finishing stand Fi+1:

$$t_{Fi,x,p} = t_{Fi,0} + \sum_{j=J+1}^{J_p-1} \Delta t_{h_i,j} + \frac{\Delta L_{J_p} - \delta L_{h_0}}{f_{v,h_i} \cdot v_{h_i,J}} + \frac{\Delta p}{f_{v,h_i} \cdot v_{h_i,J_p}} \quad \text{with}$$

$$p = \sum_{j=J+1}^{J_p-1} \Delta L_{h_i,j} + (\Delta L_{J_p} - \delta L_{h_i}) + \Delta p$$

Time when strip segment $L_{h_0,x}$ leaves roughing stand R:

$$t_{h_0,x} = t_{R,x} = t_{R,0} + \sum_{j=1}^{J-1} \Delta t_{h_0,j} + \frac{\delta L_{h_i}}{f_{v,R} \cdot v_{h_0,J}}$$

Time when strip segment $L_{h_0,x}$ passes a certain position p between roughing stand and first finishing stand:

$$t_{h_0,x,p} = t_{R,0} + \sum_{j=J+1}^{J_p-1} \Delta t_{R,j} + \frac{\Delta L_{J_p} - \delta L_{h_0}}{f_{v,R} \cdot v_{h_0,J}} + \frac{\Delta p}{f_{v,R} \cdot v_{h_0,J_p}} \quad \text{with}$$

$$p = \sum_{j=J+1}^{J_p-1} \Delta L_{h_0,j} + (\Delta L_{J_p} - \delta L_{h_0}) + \Delta p$$

### Internal values

*j,k* Index strip segment [1]

$J, K, J_p$ Number of strip segments [1]

$\delta L_{h_i}$ Remaining length of strip segment [ft -> m]

$\Delta p$ Remaining length of distance to a certain plant location [ft -> m]

### Calculation sequence

The calculation is done straight forward.

### References

none

## 5.6 Adaptation of Thermal Work Roll Crown

### Description

The thermal work roll crown is mainly influenced by two effects:

- temperature rise due to the heat flow from the material into the work roll
- temperature drop due to the heat flow from the work roll to the coolant of the roll cooling system

The idea is to calibrate the stand after a work roll change with cold rolls which is normal procedure. Then roll a small number of materials (e.g. 5) under defined and constant conditions in order to get the work rolls heated up. Then calibrate the stand again and calculate the variation in the work roll diameter out of calibration data. Then cool the work rolls down with the work roll cooling system during a certain time period (e.g. 10 min) and repeat the calibration and calculation procedure.

### Input values

| | |
|---|---|
| $s_{0,cold}$ | Calibration screw down position for cold work rolls [in. -> mm] |
| $s_{0,Heat}$ | Calibration screw down position for heated up work rolls [in. -> mm] |
| $s_{0,Cool}$ | Calibration screw down position for cooled down work rolls [in. -> mm] |
| $k_{C,old}$ | Old coefficient cooling [1] |
| $k_{H,old}$ | Old coefficient heating [1] |
| g | Learning rate [%] |

### Output values

| | |
|---|---|
| $k_{C,new}$ | New coefficient cooling [1] |

$k_{H,new}$ New coefficient heating [1]

**Submodels:**

Thermal work roll model

**Model equations:**

Variation in work roll radius from cold to heated up rolls measured with the aid of the screw down:

$$\Delta R^{*}_{WHeat} = (s_{0,Heat} - s_{0,cold}) / 4$$

Variation in work roll radius from heated up to cooled work rolls measured with the aid of the screw down:

$$\Delta R^{*}_{WCool} = (s_{0,Heat} - s_{0,Cool}) / 4$$

Heat flow from work roll to coolant of the cooling system is determined by:

$$\alpha_{Ceff} = \frac{\varphi_C}{360} \cdot \alpha^{*}_{c} \cdot k_C$$

The variation in work roll radius due to cooling can be calculated as follows:

$$\Delta R_{WCool} = \Delta R_{WCool}(\alpha_{Ceff}(k_C))$$

The inversion of the above mentioned function which is done numerically and the measured work roll radius leads to improved $k_C$ which is then inherited:

$$k_C = k_C(\Delta R^{*}_{WCool})$$

$$k_{C,new} = (1 - \frac{g}{100}) \cdot k_{C,old} + \frac{g}{100} \cdot k_C$$

Heat flow from hot strip to the work roll is determined by:

$$k_{eff} = k_{eff}^{*} \cdot k_H$$

The variation in work roll radius due to heating and cooling can be calculated as follows:

$$\Delta R_{WHeat} = \Delta R_{WHeat}(k_H, \alpha_{Ceff}(k_C))$$

Because $k_C$ has been calculated according to the cooling of the work roll it is kept constant. The inversion of the above mentioned function which is done numerically and the measured work roll radius leads to improved $k_H$ which is then inherited:

$$k_H = k_H(\Delta R_{WHeat}^{*})$$

$$k_{H,new} = (1 - \frac{g}{100}) \cdot k_{H,old} + \frac{g}{100} \cdot k_H$$

### Internal values

| | |
|---|---|
| $\Delta R_{WHeat}$ | Work roll radius variation due to heating [in. -> mm] |
| $\Delta R_{WCool}$ | Work roll radius variation due to cooling [in. -> mm] |

### Calculation sequence

The calculation is done straight forward.

### References

none

## 5.7 Adaptation of Work Roll Wear

### Description

The actual work roll wear after a rolling campaign can be measured at the grinding machine. The adaptation of the wear coefficient can be done by the comparison of the measured with the predicted wear.

### Input values

| | |
|---|---|
| $\Delta R^{*}_{WWear}$ | Measured work roll wear [in. -> mm] |
| $\Delta R_{WWear}$ | Predicted work roll wear [in. -> mm] |
| $k_{Wear,old}$ | Old wear coefficient [1] |
| g | Learning rate [%] |

### Output values

| | |
|---|---|
| $k_{Wear,new}$ | New wear coefficient [1] |

### Submodels:

none

### Model equations:

The comparison of measured work roll wear and the predicted leads to an improved wear coefficient which is inherited:

$$k_{Wear} = k_{Wear,old} \cdot \frac{\Delta R^{*}_{WWear}}{\Delta R_{Wear}}$$

$$k_{Wear,new} = (1 - \frac{g}{100}) \cdot k_{Wear,old} + \frac{g}{100} \cdot k_{Wear}$$

### Internal values

none

### Calculation sequence

The calculation is done straight forward.

### References

none

## 5.8 Fit of Mill Stretch Curve

### Description

The recorded mill stretch measurements which forms a curve is approximated by a quadratic function near the origin and a linear function for larger roll force measurements.

### Input values

$F_{R,j}$ Roll force measurement [lb -> kN]

$s_j$ Measurement of screw down positions [in. -> mm]

### Output values

$a_1, a_2, s_x$ Parameter mill stretch curve
[kN/mm, kN/mm2, mm -> lb/in., lb/in.2, in.]

### Submodels:

none

### Model equations:

The mill stretch curve is approximated by the following approach:

$$F_Q(s) = a_1 \cdot s + a_2 \cdot s^2 \quad \text{for} \quad s < s_x$$

$$F_L(s) = -a_2 \cdot s_x^2 + (a_1 + 2 \cdot a_2 \cdot s_x) \cdot s \quad \text{for } s \geq s_x$$

The calculation of the coefficients is done by a regression analyses which minimises the following sum

$$S = \sum_{j=1}^{J_x} (a_1 \cdot s_j + a_2 \cdot s_j^2 - F_{R,j})^2 + \sum_{j=J_x+1}^{J} (-a_2 \cdot s_x^2 + (a_1 + 2 \cdot a_2 \cdot s_x) \cdot s_j - F_{R,j})^2$$
$$\text{with} \quad s_x = s_{J_x}$$

The inverse function is calculated as follows:

$$s_Q(F_R) = -\frac{a_1}{2 \cdot a_2} + \sqrt{\frac{a_1^2}{4 \cdot a_2^2} + \frac{F_R}{a_2}} \quad \text{for } F_R < F_{R,x}$$
$$s_L(F_R) = \frac{F_R + a_2 \cdot s_x^2}{a_1 + 2 \cdot a_2 \cdot s_x} \quad \text{for } F_R \geq F_{R,x}$$
$$\text{with } F_{R,x} = F_L(s_x)$$

### Internal values

| | |
|---|---|
| $s$ | Srew down position [in. -> mm] |
| $F$ | Roll force [lb -> kN] |
| $S$ | Sum of residuals [$lb^2$ -> $kN^2$] |

### Calculation sequence

The calculation of $S(J_x)$ is done by incrementing $J_x$ till the absolute minimum of $S$ is attained.

### References

none

# 6. Look-up Tables

## 6.1 Looper

### Description

The look-up table for the looper includes the specific looper tensions and initial angle of looper.

### Input values

| | |
|---|---|
| $i_{stcl}$ | Steel grade class [1] |
| $h$ | Strip thickness [in.] |
| $i_{stno}$ | Stand width [in] |

### Output values

| | |
|---|---|
| $f_{ten}$ | specific strip tension [psi -> N/mm^2 ] |
| $\varphi$ | initial looper angle |

## 6.2 Descaler

### Description

The look-up table for the descaler includes the descaling pattern.

### Input values

$i_{stcl}$ Steel grade class [1]

### Output values

*pat* descaling pattern [1]

## 6.3 Interstand Cooling

### Description

The look-up table for the interstand cooling includes the cooling pattern for the interstand cooling and the strip length which should be cooled.

### Input values

$i_{stcl}$ Steel grade class [1]

### Output values

*pat* cooling pattern [1]

$L_{stcool}$ Strip length to be cooled [m -> ft]

# 7. Revision and Document Distribution List

| REVISION LIST | | | |
|---|---|---|---|
| **Date** | **Version** | **Author** | **Description** |
| 94-Jul-22 | V1.0 | Dvo | first draft |
| 94-Aug-31 | V2.0 | Pi,Schl | final version |
| 96-Feb-28 | as built | Bald | as built |

| DISTRIBUTION LIST | |
|---|---|
| **Version** | **Receiver** |
| V1.0 | ARMCO |
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