Improved roll pass design for long products with WICON

Rolling Library
WICON Rolling Library is a professional tool for making all the necessary calculations and simulation of the process parameters in a rolling mill. This includes roll pass design, evaluating changes to process conditions, evaluating new products or process routes as well as evaluating modifications to existing mills or new design proposals.

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Today's demands on productivity and quality in hot rolling mills for rod and wire require continuous analysis of processes and equipment. To reduce risks, time and cost in projects for the introduction of new products and the managing of new equipment, good analysis tools are required. WICON Rolling Library is a collection of programs that enable the necessary calculations and simulations of the process parameters in a rolling mill to be made. Additionally operators can test and check their own ideas as well as of the technical quotations of mill suppliers when upgrading existing mills or building new mills. The library covers all different mill layouts from single stand blooming mills and old looping trains to modern continuous mills, 3-roll blocks and 2-high finishing blocks with conceivable symmetrical groove shapes and rolling sequences which can occur when rolling finishing rounds, squares, hexagons and flats in wire rod, bar or blooming mills. It is also possible to make simulations and calculations of the slit rolling process. The DOS version of WICON has been available since 1985 and the first Windows version was released in 1998. It is now used by more than 120 companies.

The programs included are:

- Data base
  - Layout
  - Groove table
  - Rolling schedule
- Rolling
- Pass design
- Plot roll
- Graphs
- Temperatures
Data Base

Data base consists of three program modules for building up the fundamental data of mill, grooves and rolling schedules. A rolling mill layout consists of a number of motors and stands connected in various arrangements. Each specific mill can be explained with the thirteen columns shown in:

**Figure 1.** This example describes the layout of the WICMILL rod and bar mill consisting of 16 conti-stands followed by a 5-stand Kocks block with three separate driven stands and ending with two coupled stands driven by one motor.

Layout also includes data on motors, gears and tension control together with information on cooling conditions/rates in and between the stands and roll deflection characteristics of the stands. Roll deflection is used in the Rolling simulation program for calculating the empty gap (unloaded stand) and is calculated from the roll deflection value for the stand.

The resulting deflection ($\Delta G$) of the pass is the calculated roll separating force ($F$) multiplied by the mechanical deflection value ($D_{mech}$) minus the gap reduction due to the oil film layer ($D_{oil}$) for stands with oil film bearings.

$$\Delta G = F \times D_{mech} - D_{oil}$$

![Figure 1](image-url)

A schematic layout of the WICMILL rod and bar mill consisting of 16 conti-stands followed by a 5-stand Kocks block with three separate driven stands and ending with two coupled stands driven by one motor.
Groove table

Groove table covers all the different types of grooves used for rolling of rounds, squares, hexagons, flats, asymmetric grooves used in 3-high stands (see Figure 2) and slit grooves (see Figure 3). Grooves are defined in tables, one table for each type of groove. When data for a groove is entered it is also possible to directly see and print a drawing (see Figure 4).

Figure 2
Drawing of unsymmetrical groove used in 3-high stands.

Figure 3
Drawing of slit groove.

Figure 4
Table for box grooves with entered data. Just by clicking on the row a drawing is made that then can be printed.
Rolling schedule

This program describes each pass in the rolling process (see Figure 5). One row represents one pass. Data on the mill layout is loaded from the file created in the Layout module to obtain data on motor and gear ratios. Each groove is inserted in the schedule from the Groove table database. The groove dimensions are as X-Y coordinates included in the schedule.

![Rolling mill: WIGALL Rolling schedule: RD48-101](image)

**Figure 5**
A schematic rolling schedule. Each row represents one pass in the rolling process. Spread coefficient (S.C.) is value used for spread calculations in simulation program and nominal gap is the active gap during the rolling when the roll separating force.

The spread coefficient (S.C.), value used for spread calculations in the simulation program (Rolling), is automatically inserted for each pass. The S.C. depends on the geometric combination of inserted grooves in the schedule. Default values have been evaluated from a large number of passes in continuous mills when rolling plain carbon steel between 0.5 - 0.85 %C. Main reason why the values differ is that the lower values are from groove combinations in the beginning of the mill where the temperature is higher than for the groove combinations in the middle part of the mill. The nominal gap is the active gap during the rolling when the roll separating force is acting on the stand. The empty gap when the stand is unloaded is calculated in the simulation program based on the actual calculated roll separating force.
Rolling
Rolling, the main program, is a dynamic simulation program which instantaneously recalculates the conditions for the mill setup after any change of the rolling parameters. Rolling can be used to simulate and calculate process parameters to be used in the set up of the mill, to analyze rolling problems or optimize the process, use as an analyzing tool when introducing new products and equipment or as a tool for staff education. Calculations are carried out in five steps:

- Dimensions
- Speed (motor/roll revolution)
- Load, torque and power
- Temperature
- Empty gap

Dimensions are calculated as a function of geometry, material, temperature and tension. Calculations are made from billet to finished dimension using a developed spread formula. The calculation of spread is based on the Wusatowski spread formula [1], applied on Lendl’s method [2] of equivalent rectangles. The spread calculation has been modified by Morgårdshammar in order to better conform with measured width values.

Wusatowski’s spread formula at its simplest form is:

$$\frac{W_1}{W_0} = \left(\frac{H_1}{H_0}\right)^w$$

where index 0 is entering and 1 exiting. \(W\) is width, \(H\) is height, and \(-w\) is calculated as

\[-w = -10 \cdot 10^{0.56\varepsilon_w}\]

\(\delta_w\) is a form factor calculated as

$$\delta_w = \frac{W_1}{H_1}$$

and \(\varepsilon_w\) is a roll factor calculated as

$$\varepsilon_w = \frac{H_1}{D_1}$$
where $D_1$ is roll diameter in exiting pass. Since these considerations apply only to plain sections i.e. square and rectangular bars rolled between plain cylindrical rolls Lendl’s method of equivalent rectangles needs to be used (see Figure 6).

Figure 6
Schematic drawing of round - oval sequence with equivalent heights.

With the modified spread the real exit width $W_1$ is calculated as

$$W_1 = W_0 + S.F. \times S.C. \times \Delta W_c$$

Where S.F. is spread factor and S.C. is spread coefficient. S.C. is partly depending on the groove combination but it is much more dependent on the composition of the rolled material, the temperature of the material and the friction conditions between the rolls and the material. It has been evaluated from a large number of passes in continuous mills when rolling plain carbon steel between 0.5 - 0.85 %C.

S.C. values during the spread calculation are multiplied by the S.F. By entering a S.F. deviating from 1 it is possible to simulate other spread conditions than the default values. $\Delta W_c$ in previous equation is calculated as
\[ W_c = W_c - W_0 \]

where \( W_c \) is the calculated width based on geometrical conditions for exiting equivalent rectangle and are calculated as

\[ W_c = W_1^{\text{Eqv}} \times f (\Delta W_0^{\text{Eqv}}) \]

where \( \Delta W_0^{\text{Eqv}} \) is the difference between real entering width and width of the entering equivalent rectangle (see Figure 7).

\[ \Delta W_0^{\text{Eqv}} = W_0 - W_0^{\text{Eqv}} \]

and \( W_1^{\text{Eqv}} \) is equivalent exiting width calculated with Wusatowski’s spread formula as

\[ W_1^{\text{Eqv}} = W_0^{\text{Eqv}} \times \left( \frac{W_0^{\text{Eqv}}}{W_1^{\text{Eqv}}} \right)^G \]

where

\[ G = 10^{-1.269 \times \left( \frac{H_0^{\text{Eqv}}}{D_1^{\text{Eqv}}} \right)^{0.556}} \times \frac{W_0^{\text{Eqv}}}{H_0^{\text{Eqv}}} \]

Figure 7
\( W_0^{\text{Eqv}} \) is difference between real entering width and width of entering equivalent rectangle.

The summarized equation for calculation of real exit width will be

\[ W_1 = W_0 + \text{S.F.} \times \text{S.C.} \times \left[ W_0^{\text{Eqv}} \times \left( \frac{H_0^{\text{Eqv}}}{D_1^{\text{Eqv}}} \right)^{10} \times 1.269 \times \left( \frac{H_0^{\text{Eqv}}}{D_1^{\text{Eqv}}} \right)^{0.556} \times \frac{W_0^{\text{Eqv}}}{H_0^{\text{Eqv}}} \right] \times f (W_0 - W_0^{\text{Eqv}}) - W_0 \]
Speed (motor/roll revolution)
As well as having a proper pass design in order to get good surface quality, tolerances and high production yield, it is of great importance to set an accurate speed and motor revolution relationship between the stands/motors in a continuous mill in order to control interstand tension. Calculation of speed and motor revolution is made from finishing exit speed upstream of the billet according to the principle of constant mass flow. The speed calculation is a function of finishing speed, area of the bar, roll diameter, tension and forward slip.

The roll revolution \( n \) is calculated from the exit speed by the formula

\[
\frac{n}{\pi \times D_{\text{eff}}} = \frac{v_{\text{Exit}}}{\pi \times D_{\text{eff}}}
\]

\( D_{\text{eff}} \) is the effective roll diameter, which is calculated based on the process conditions at the neutral point. This is the point between entry and exit, in which the horizontal component of the circumferential speed of the roll is equal to speed of the bar. The roll diameter varies with the depth of the groove along the width of the groove (see Figure 8). The diameter at the groove bottom \( D_g \) is smaller than the outer diameter \( D_o \). The circumferential speed at the groove bottom is therefore smaller than the circumferential speed at the roll barrel. Each part of the cross-section of the bar must of course have the same speed in the rolling direction. This means that there must be one roll diameter, the working diameter \( D_w \), which is generating that speed. The neutral point \( D_w \) is situated between the groove bottom diameter \( D_g \) and the diameter \( D_l \) at the intersection between the groove and the bar edge. \( D_w \) is therefore a dynamic variable and not a constant based on the groove depth as in common level 2 systems.

![Figure 8](image)

At the neutral point the working diameter \( D_w \) is situated between the groove bottom diameter \( D_g \) and the diameter \( D_l \) at the intersection between the groove and the bar edge. \( D_w \) is therefore a dynamic variable.
Circumferential speed \( v \) is calculated as:

\[
v = \pi \times n \times D
\]

where \( n \) is roll revolution and \( D \) is diameter.

The mass flow must be constant along the contact length, which means

\[
v_{in} \times A_{in} = v_{Neutral} \times A_{Neutral} = v_{Exit} \times A_{Exit}
\]

or

\[
v_{Exit} = v_{Neutral} \times \frac{A_{Neutral}}{A_{Exit}}
\]

where \( v_{Neutral} \) is the circumferential speed created by the working diameter at the neutral point and \( \frac{A_{Neutral}}{A_{Exit}} \) is called forward slip (F.S.).

The exit speed \( v_{Exit} \) is then

\[
v_{Exit} = \pi \times n \times D_{w} \times F.S.
\]

The definition of the \( D_{eff} \) in the WICON Rolling Library is

\[
D_{eff} = D_{w} \times F.S.
\]

\( D_{eff} \) can be larger or smaller than the outer roll diameter. The reason for that is the F.S., which, in many Level 2 control systems, is totally neglected although it is of greatest importance for the correct speed setup of a mill. Both F.S. and \( D_{w} \) increase with increasing reduction by decreasing the gap for a given groove. The conclusion is that the \( D_{eff} \) for a groove changes when the roll gap is changed while the conventionally used \( D_{w} \) is constant and independent of gap setting and the spread properties of the rolled material.

The exiting volume \( V \) of the rolled material must in a continuous mill be the same in all stands.

\[
V_1 = V_2
\]

or

\[
v_1 A_1 = v_2 A_2
\]

Applying a tension between two stands means that the motor revolution of the second stand is increased in comparison with the motor speed for tension-free rolling. When applying a tension of 5% between stand 1 and 2 only, the motor speed of stand 2 is increased by \( \sim 5\% \). The exiting speed will increase from \( v_2 \) to \( \sim 1.05 \times v_2 \). As the exiting volume from each stand must be constant, the exiting area \( A_2 \) must decrease to \( \sim A_2/1.05 \). As the gaps are the same in all cases, the decrease of the exiting area in stand 2 must be related to a smaller width of the exiting bar. The tension will therefore decrease the spread in stand 2. As the tension changes the width it also affects the forward slip, the working diameter and the neutral angle. This is not taken into account in the explanation above, but is of course included in the process calculations in the programs.
The leading and tail end of the bar will always be rolled without tension, as the tension can only work when the bar is in contact with at least two stands at the same time. That means that the ends will be wider than the rest of the bar which has been rolled in a steady state condition. The difference in width along the bar will be larger the greater the tension and the greater number of stands controlled by low tension control in separate driven stands or the more stands there are in a block. The length of the width difference is dependent on the distances between the stands and the reductions in each stand.

In a block the rolling equipment is mounted on a framework in a continuous arrangement and the stands are driven by one motor. This kind of arrangement requires rolling with tension between the stands which are achieved by decreasing the gear ratio of each stand in comparison with the ratio which would have been selected for tension-free rolling. When the balance is disturbed by changing the gaps in any of the stands or the entry area into the block, it is not possible to change the speeds as the gear ratios are fixed. The only way to find a new balance is that the elongation values are changed in such a way that the principle of constant volumes remains. This new balance is calculated by the program and reported as changes in tension between the stands. Unless the changes do not turn the tension to a compression, the width of the bar will only be affected by changing the entry section or by changing the gap of the first or last stand in the block. This is a very complicated interactive calculation which has proved to be very accurate when tested on measured values. The calculated motor revolution deviations are within 1.5%, which means that the speed control system will be balanced much quicker than with conventional setup data. The first billet normally runs within tolerances compared to 5 – 8 test billets for a conventional setup.

Load, torque and power
The calculation of load, torque and power is based on the Sims formula[3] from billet to finishing dimension as a function of geometry, grade of rolled material, temperature and tension. The flow stress data are collected from Weber[4] and from Cook and McCrum [5]. For each material there are eight graphs for the natural strain values between 0.05 and 0.7. Each graph covers the temperature range 900 - 1200 °C and the mean strain rate 1.5 - 100 1/sec. The programs make an interpolation of the data in the graphs in order to find the flow stress for the specific pass conditions. The program includes twelve base materials. For each material it is possible to add a ‘Flow stress multiplication factor’ to be able to simulate rolling with material that is not in the material database but similar to one of those.

Temperature
The temperature calculation is based on a method developed at Morgårdshammar. The calculation is a function of power, dimension and heat transfer coefficients. The method is a simplified model of the numerical solution of the differential equations of heat transfer in a solid bar. The calculated temperature is the weighted mean temperature over the cross section, which are used to calculate the most accurate flow stress value to be used in the load, torque and power calculation. The program calculates the entry temperature for each pass going out from the given entry temperature in the first pass and the cooling conditions specified.

Empty gap
Empty gap is calculated as a function of load, dimensions, mechanical roll deflection and oil film factor. The calculation of the empty gap setting is done in order to get the desired active gap for the loaded stands. The resulting deflection of the pass is the calculated load (roll separating force) multiplied by the mechanical deflection value minus the gap lessening due to the oil film layer for stands with oil film bearings. The oil film layer is mainly a function of the roll revolution. The oil film is counteracting the mechanical deflection.
Results from calculations
The main module Rolling is a dynamic simulation program which instantaneously recalculates the conditions for the mill setup after any change of the rolling parameters e.g. the gap changing for material with different spread properties. All the relevant calculations are instantly carried out and results are displayed as in which shows one rolling sequence and how the grooves are filled. The grooves are displayed upon one another in the way the bar enters into the next groove in order to better understand the spread conditions. The red lines in the grooves are the free bar edge. It is also possible to present results graphically directly in Rolling or in the Graphs modules.

Results that are presented are:
- Empty gap
- Height and width are presented as cold or hot dimensions. The cold dimension is the hot dimension divided by the expansion factor for the actual temperature and the actual material for the flow stress data.
- Area reduction or elongation. The reduction is the area reduction in % while the elongation is the ratio $A_{\text{entry}} / A_{\text{exit}}$ in the pass.
- Effective diameter or Diameter difference. This is used for calculating the exit speed from a pass, see Speed (motor/roll revolution). The diameter difference $D_{\text{eff}}$ is the effective roll diameter $D_{\text{eff}}$ minus outer roll diameter $D$.

$$\Delta D_{\text{eff}} = D_{\text{eff}} - D$$

The diameter difference is to be compared with 'The groove factor' but is much more accurate as it includes the influence of the forward slip.
• Motor- or roll revolution. The revolution is calculated from the finishing speed. If a calculated revolution for a pass exceeds the restrictions given in the loaded Layout file (e.g. max. motor revolution, max. or min. loop growth) the program tries to find a speed that can be accepted by the Layout specifications.

• Speed, exit speed from each pass.

• Tension between stands. The tension between two stands has a major impact on the spread in the second stand, which will be evident by studying the change of the bar width in the second stand when changing the tension value.

• Entry temperature. When the program finds a given temperature for a pass it uses this temperature for the load calculation and calculate the next temperatures till it finds another given temperature and so on.

• Load, Torque and Power. Load is the roll separating force acting during the deformation of the rolled material. Torque is the total rolling torque required for deformation of the rolled material. Power is the power required for deformation of the rolled material. Power max, Power mean and Power available are also calculated. Power max is the one combination of all interacting power values which has the highest value, including the empty running power of the drive equipment (~10% of the rated maximum power of the motor). The mean power \( P_{\text{Mean}} \) is the root mean square value calculated according to

\[
P_{\text{Mean}} = \sqrt{\frac{P_1^2 \times t_1 + P_2^2 + t_1 t_2 + \ldots + P_n^2 \times t_{i-1} t_i}{t_1 + t_2 + \ldots + t_{i-1} t_i}}
\]

\( P_i \) is the interacting power combination acting during the time \( t_i \). The available power \( P_{\text{Available}} \) of a DC motor is a function of motor revolution and the rated maximum power. The maximum power \( P_{\text{MotorMax}} \) is available only between the base revolution and the maximum revolution. When rolling with a motor revolution \( n \) below the base revolution \( n_{\text{Base}} \), the available power is

\[
P_{\text{Available}} = \frac{P_{\text{MotorMax}} \times n}{n_{\text{Base}}}
\]

Available power for a standard AC motor is the rated motor power.

• Angle of bite, the program is flagging for values larger than 25°. Values larger than 25° can be accepted in reality depending on the rolling conditions.

• Bar area, the cold or hot cross section area of the bar after the pass.

• Bar length, the cold or hot length of the bar after the pass.
Pass design
The Pass Design module is the program for designing new grooves in existing rolling schedules as well as producing completely new rolling schedules. Redesigning single grooves in an existing rolling schedule is made by just a mouse click. In Pass design there are in-built general rules of design that automatically create new grooves in a mouse click. A comparable calculation that is made in Rolling which gives the opportunity to see how different groove geometric will affect the rolling directly.

Plot roll
Plot roll is a CAD program specially designed for making groove drawings, roll drawings (see Figure 10) and groove plans. It is easy to use and has also an interface with other common CAD programs. It can also be used as the initial data for CAM programs. When a roll drawing is created, groove dimension is called from the Groove database and automatically added to the roll drawing that then directly can be printed or saved as CAD file.

![Groove dimensions are called from the Groove database and automatically added in to the roll drawing.](image)
Roll drawings can directly be printed or saved in CAD file format.

**Graphs**

Graphs are a program for displaying multiple function, multiple dimension process data graphs, (see Figure 12). The graphic presentation makes it easier to understand and evaluate the process conditions in the mill and how the different finishing dimensions are interacting.

Graphs module showing the Power graph.
Temperatures

This program calculates the temperature distribution over the cross section in a solid body by heating and cooling as a function of time. The mathematical model used is a numerical solution of the differential equations of heat transfer in a solid bar. The thermal flow inside the bar is a function of the thermal conductivity and the thermal diffusivity of the selected material. The values are a function of the temperature and the composition of the material. The values of the build in material data library are taken from a BISRA report [6]. The heat to be removed from the surface or the heat to be absorbed by the surface is a function of the temperature difference between surface and surrounding media and the applied heat transfer coefficient. The total heat transfer coefficient by cooling consists of three parts:

- Radiation $a_r$: the heat transfer coefficient depending on radiation is calculated in the program and is about 60 W/ (m² °C) for a bar surface temperature of 1000 °C.
- Convection $a_c$: the heat transfer coefficient depending on natural convection is of the magnitude 30 W/ (m² °C). Forced air cooling may increase the convection with another ~ 100 W/ (m² °C).
- Water cooling $a_w$: a lot of investigations have been carried out in order to evaluate the heat transfer coefficient by forced water cooling. Depending on the design of the water cooling pipes and the flow and pressure of water, it is possible to reach values between 10,000 and 50,000 W/ (m² °C). Normal values for the water cooling section between the finishing stand and the laying head in high speed wire rod mills are 10,000 – 25,000 W/ (m² °C). Values above 25,000 W/ (m² °C) are reached in the special cooling equipment for direct heat treatment of rebars.

The program can also be used for evaluation of actual heat transfer coefficients by comparing measured temperature values with the calculated values for different given heat transfer coefficients.
Conclusions
All rolling mills have problems regarding product quality, production yield, or both. Most are also continuously investigating the possibility to widen the product range and/or increase production. Only by having a good knowledge of the process parameters is it possible to make the right decisions and take the right measures for making the desired improvements. WICON Rolling Library is a professional tool for making all the necessary calculations and simulation of the process parameters in a rolling mill. The easy-to-use concept and the fact that the programs are self educational makes it possible for all staff involved in production to test ideas for improving mill conditions.

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