MODELS FOR FLATNESS OF HOT ROLLED STRIPS AND SHEETS[1]

Daniel Hajduk[2]
Felipe Gustavo Bernardes[3]

Summary
The paper deals with essential models of control system to reach the desired profile and flatness of hot rolled strips. In the first part basic terms are defined – strip crown, flatness and mutual relation of those two parameters. Flatness criterion suitable for hot rolling was mentioned. It is based on one dimensional spring-beam model with nonlinear springs, suitable for 4-high and 6-high mills. Both vertical deflections of the roll stack as well as jump (vertical displacement) of work rolls are considered. The model is suitable for on-line control. In the second part a bending force model working with given draft schedule in described. Linear programming (simplex method) has been used to find correct sequence of crowns keeping the strip flat. On an example a comparison of rolling without bending and with bending forces, calculated by the described model in demonstrated. The developed models have been implemented in control system of the strip mill P 1500 in Mittal Steel Ostrava. Process testing has shown improvements of the strip crown (better accordance between predicted and measured values) and improvements of strip flatness.
Key words: Flatness; Roll gap deformation; Roll bending.

MODELO DE PLANICIDADE APLICADO À LAMINAÇÃO DE TIRAS

Resumo
Este trabalho trata de modelos de sistema de controle de forma e planicidade de materiais laminados à quente. Na primeira parte do trabalho são definidos conceitos básicos: coroa e planicidade da tira e a interação destes dois parâmetros. Descreve-se um critério de planicidade aplicável aos materiais laminados à quente e um algoritmo de cálculo do perfil da tira. Sendo este último baseado em um modelo não linear de feixe-de-molas unidimensional, aplicável em laminadores "4-*high*" e "6-*high*". Tanto as deflexões quanto os deslocamentos verticais dos cilindros de trabalho são considerados. O modelo também é aplicável para realizar controle *on-line*. Na segunda parte apresenta-se um modelo de força de *bending* para uma dada seqüência de passes. O método de programação linear (método *simplex*) é utilizado para determinar a sequência correta de coroas para obter coroa plana na tira. Apresenta-se um exemplo de aplicação do modelo onde são comparadas condições de laminação com e sem uso das forças de *bending*. Os modelos desenvolvidos foram implementados no LTQ 1500 na Mittal Steel Ostrava. O processo de testes mostrou melhoria no controle da coroa (melhor aderência entre os valores previstos e medidos) e na forma do material laminado.
Palavras-chave: Laminação; Planicidade; Deformação no contato; Bending

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2 *ITA Ltd., Martinská 6, 709 00 Ostrava, Czech Republic, mail@ita-tech.cz*
3 *Aços Villares S.A., Villares RMS, Pindamonhangaba, São Paulo, Brasil*

1 INTRODUCTION

In today's market for flat rolled products, quality has become the dominant factor in determining the competitive strength of a metal producer. From the point of view of product quality profile and flatness are important geometrical parameters of flat rolled products. The market requirements for maintaining tighter strip profile tolerances have stimulated an expansive of efforts for the development of new technology for strip profile and flatness control.

As a result of these efforts, various strip profile sensors and actuators have become available for rolling mill applications. It has become obvious that both mill builders and metal producers need more knowledge and understanding about the factors that effect strip profile and flatness, thus enabling them to objectively select the most adequate strip profile control technology for each particular application.

Since the strip exit profile is primarily a function of the deformed roll gap profile the problem of modelling profile and flatness is essential one of modelling the deformed roll gap profile.

2 RELATION BETWEEN STRIP CROWN AND FLATNESS

Strip crown is defined as:

$$Cr = tc - tx$$

where: tc ... [mm] strip thickness in the centre,
tx ... [mm] strip thickness in the distance x [mm] from its edge.

Strip crown is significantly influenced by the form of the roll gap. It depends particularly on:

- separating force,
- bending force,
- profile of rolls (thermal camber, grinding, wear)

Sequence of crown in passes has decisive influence on flatness. If the inequality (1)[1,2] will be fulfilled, the strip remains flat. If it to be the contrary, central buckles or edge waves originate (Figure 1).

$$-80\left(\frac{h}{b}\right)_i^{1,86} < \left(\frac{Cr}{h}\right)_{i-1} - \left(\frac{Cr}{h}\right)_i + \varepsilon_r < 40\left(\frac{h}{b}\right)_i^{1,86} \qquad (1)$$

where $\left(\frac{Cr}{h}\right)_{i-1}$ ... Strip crown to thickness ratio in entry side into pass i,

$\left(\frac{Cr}{h}\right)_i$ ... Strip crown to thickness ratio in exit side from pass i,

ε_r ... Residual longitudinal strain in strip,

$\left(\frac{h}{b}\right)_i$ ... Thickness to width ratio in exit side from pass i.

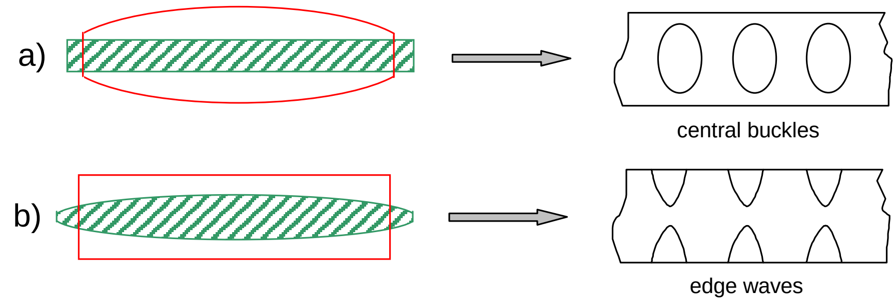


Figure 1: Change of crown leading to central buckles/edge waves.

3 ROLL STACK DEFLECTION MODEL

Scheme of the upper/lower roll stack model is obvious from Figure 2 and Figure 3. Roll deformations consist of two basic components, bending of the roll centre lines (beams) and the local deformation in contact with another rolls or rolled strip (springs). First component is linear with regard to the vertical loads, but the second one (contact deformation of rolls) is a non-linear one. So the springs connecting rolls are nonlinear and they can be removed if zero or negative pressure between rolls appears.

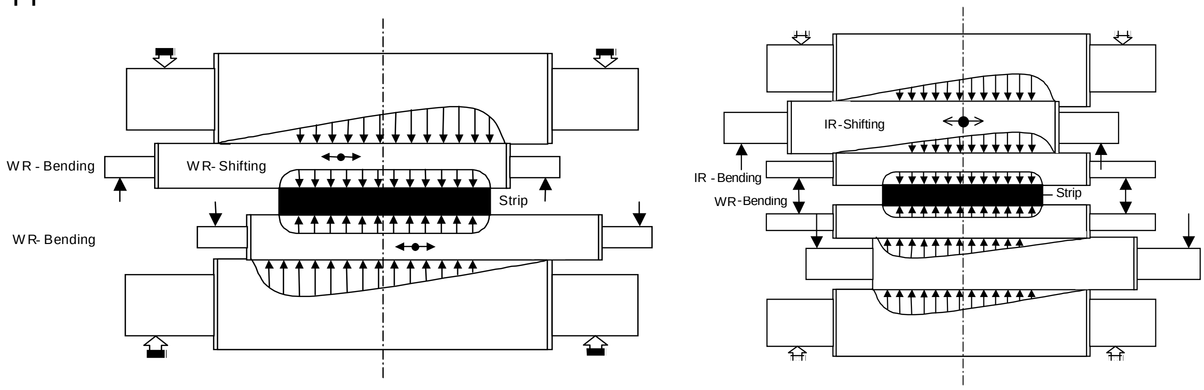


Figure 2: Scheme of 4-high and 6-high mills with actuators.

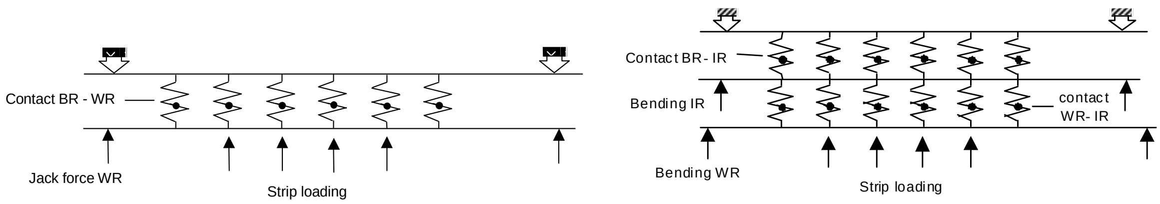


Figure 3: Scheme of 4-high and 6-high spring-beam deflection model.

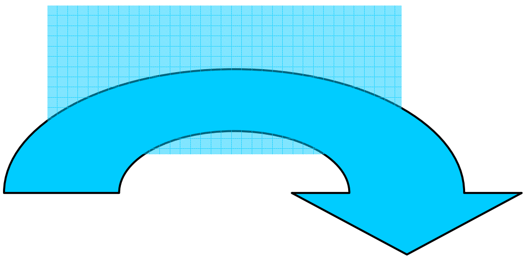
Roll bending (for known strip loading) is calculated by finite element method using 1-D Hermite beam element with influence of shear forces[3]. The element can be cylindrical or conical, consisting of one or two different materials (sleeved rolls). The loading on one element is represented as specific force with trapezoidal form.
Contact deformation between work and intermediate rolls is expressed by modified Herzian formula for infinite cylinders in contact.[4] Work roll flattening model[5] gives the elastic contact deformation of work roll in contact with a rolled strip. Work roll flattening superimposed on deflection of work roll axis gives a form of loaded roll gap.

In hot rolling when the elastic spring back of the strip can be neglected, the roll gap form can be considered to be identical with the strip profile.
Deformation of the roll stack for known rolling force is solved in iterative procedure. Deformation of roll surfaces in contact is expressed in terms of unknown polygonal loading. From the condition of the identical deflection of both rolls in contact and from the static equilibrium for the unsupported rolls (work and intermediate) the unknown contact loading between rolls can be obtained.
In case of unknown rolling force the strip roll gap model is to compute vertical forces acting on the work roll. Those data can be calculated from technological and material parameters and unknown strip exit profile. Coupling (Figure 4) of the strip roll gap model with roll stack bending model enables to solve the strip exit profile for complex cases. The coupling is done in iterative procedure.

1. Strip force – constant on strip.
2. Calculation of the upper roll stack deflection.
   Calculation of the lower roll stack deflection.
   Calculation of strip (equivalent) exit profile.
3. Calculate new strip force for the strip exit profile.
4. Check the strip exit profile (previous and recent iteration)
   if under limit – stop,
   if over limit – continue with step 2.

4 FLATNESS MODEL FOR BENDING

Rolling without waves (with full or restricted recrystallisation) is described by inequality (1). The first task is to determine for the known drafting strip crowns, that it will be in flatness region. In general there are endless solutions let us find the one having minimum ratio (c/h) in every pass and the value of strip crown in the last pass must be equal to target crown. This can be done e.g. by simplex method. Finally, from the found sequence of crowns bending forces can be calculated from (2). The whole algorithms can be seen in Figure 5.



$$\mathbf{c = c_A + S_B \cdot F_B} \qquad \mathbf{(2)}$$

c_A… Strip crown without bending
F_B…. Bending force
S_B…. Sensitivity of crown towards bending force

Figure 4: Coupling of roll stack deflection model with roll gap model.

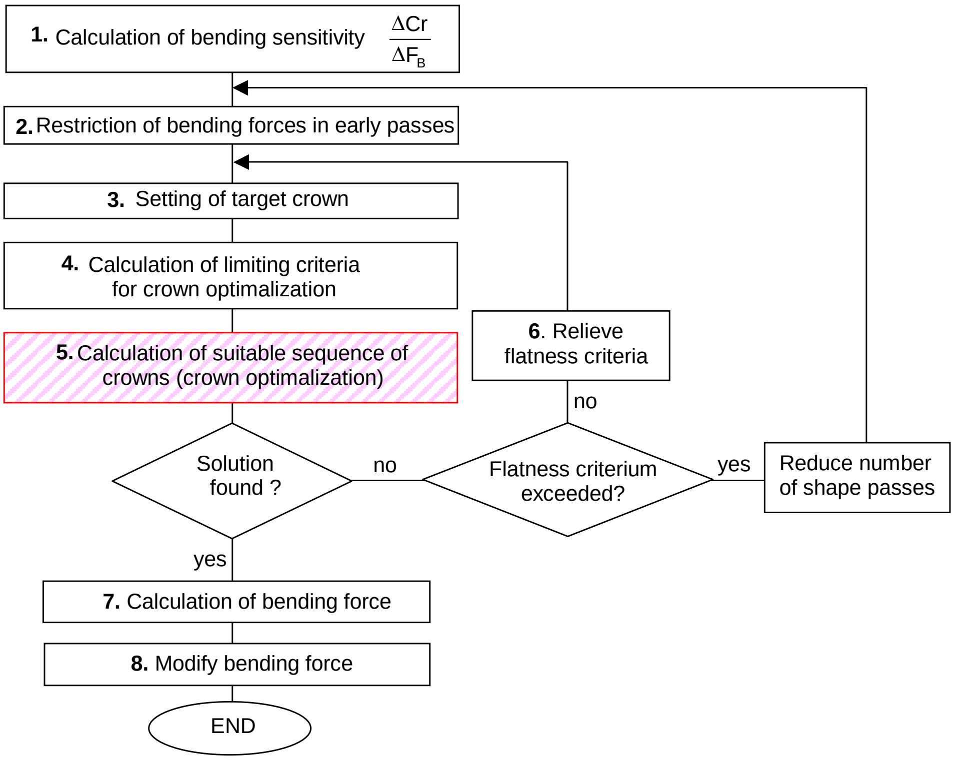


Figure 5: Flow chart of bending force model.

For the control of bending other models calculating the actual profile of WRs and BuRs are important (Figure 6).

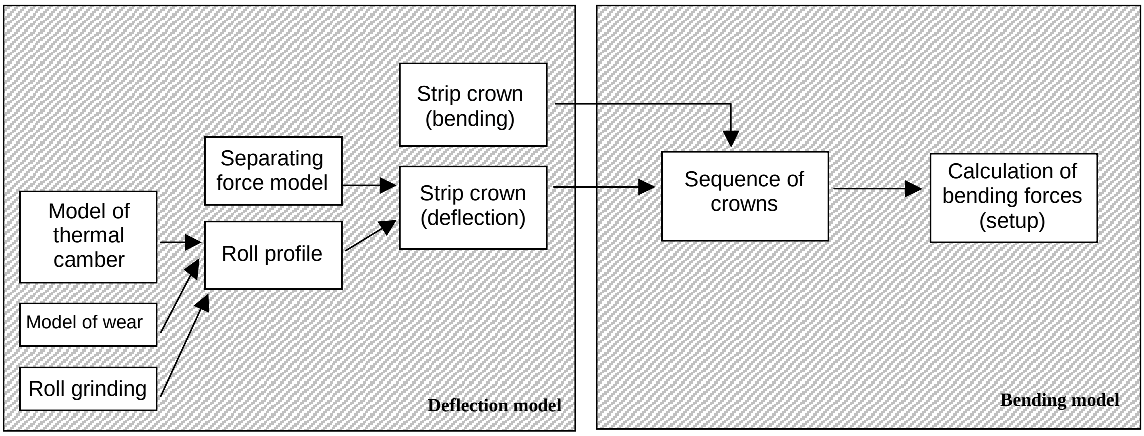


Figure 6: Key models for flatness.

5 ON-LINE AND OFF-LINE USE OF THE SOFTWARE

Presented models are available for on-line and off-line usage. On-line version can setup bending force for every stand of the finishing HSM to obtain target crown and to get the strip flat. Bending model can work rather independently from existing control system (taking only the necessary data) or be fully integrated in it.
The off-line version can solve large scale of problems. The typical application is off-line monitoring of existing setup of bending and shifting. This can detect problems in existing control system like:

- unsuitable setup of bending and shifting,

- too high bending in early passes,
- ill calculated thermal chamber of WRs,
- unsuitable bending strategy,
- uncorrect models of material hardening (recrystallization).

The diagrams (Figures 7, 8) show the influence of bending in terms of crowns (Figure 7) and in space of flatness (per unit crown change versus thickness) (Figure 8). It is evident, that without bending edge waves originate in this case. Using bending all the rolling is within flatness region.

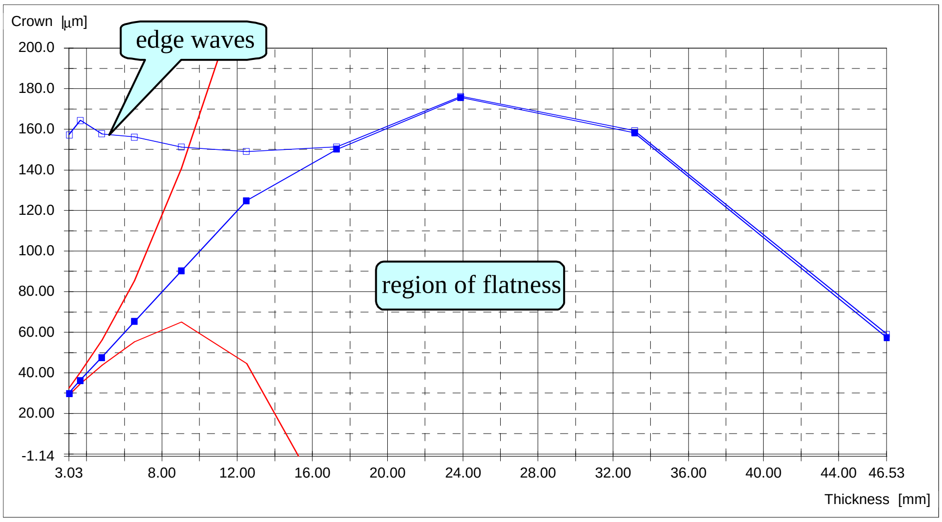


Figure 7: Sequence of strip crowns (comparison of rolling with and without bending).

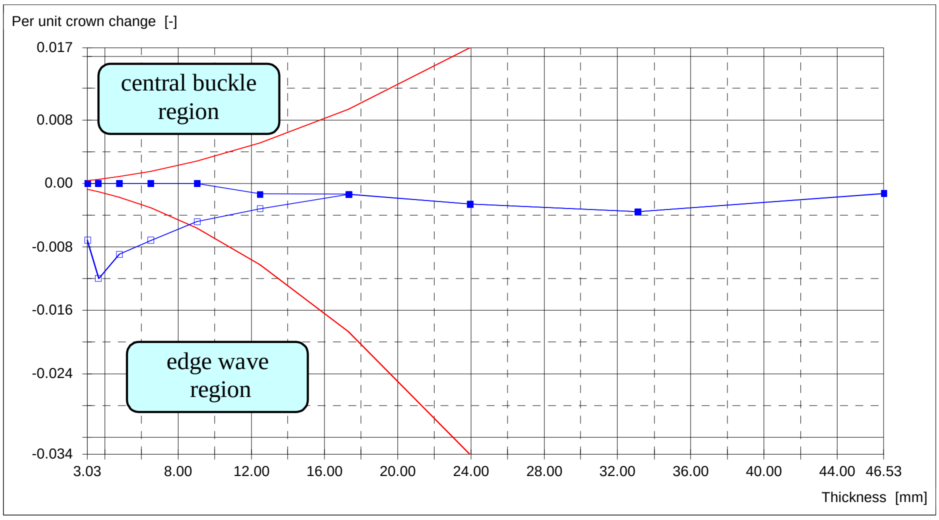


Figure 8: Rolling with bending and without bending (in space of flatness).

Another possibility of the models is optimalization of work roll grinding. Sometimes there are several different grinding of work rolls used for different strip width and steel quality. Computer simulation can find universal grinding or at least reduce the number of grindings. It can help to find suitable grinding of the BuR, to reduce the contact load on the edges of the barrel and lessen the danger of forming spalls and cracks.

The off line version can produce so called parametric studies, showing the influence of one or more parameters on strip crown (Figures 9, 10), strip profile and other important parameters –sensitivities and distribution of load between WR and BuR.

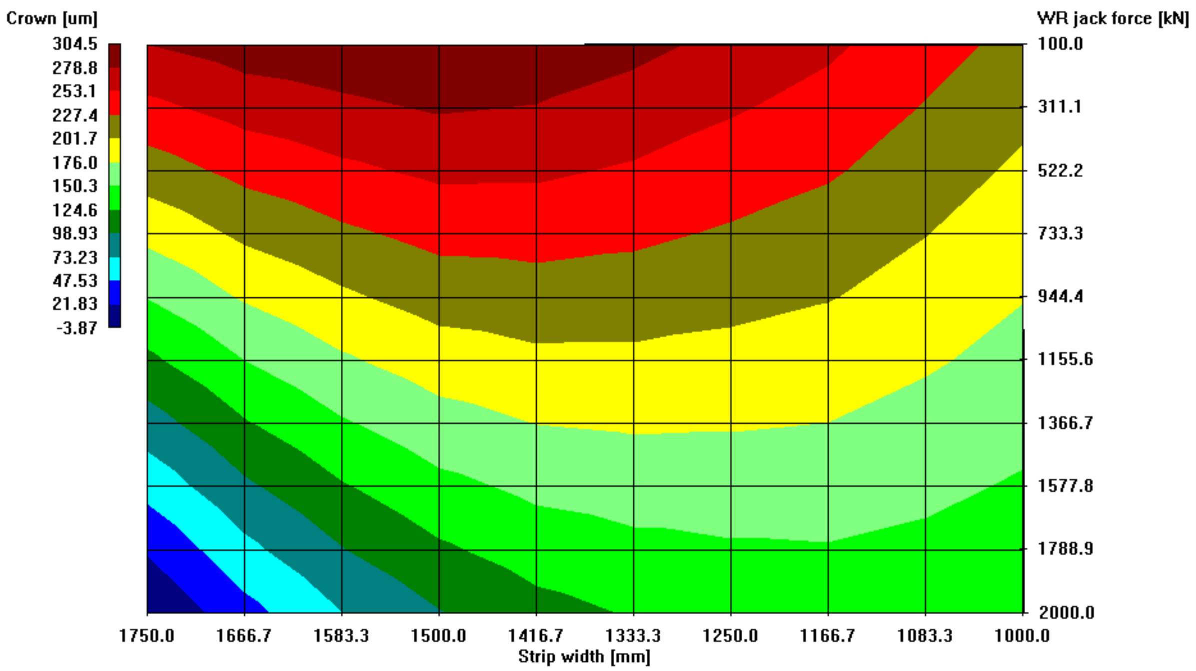


Figure 9: Strip crown versus strip width and WR jack force.

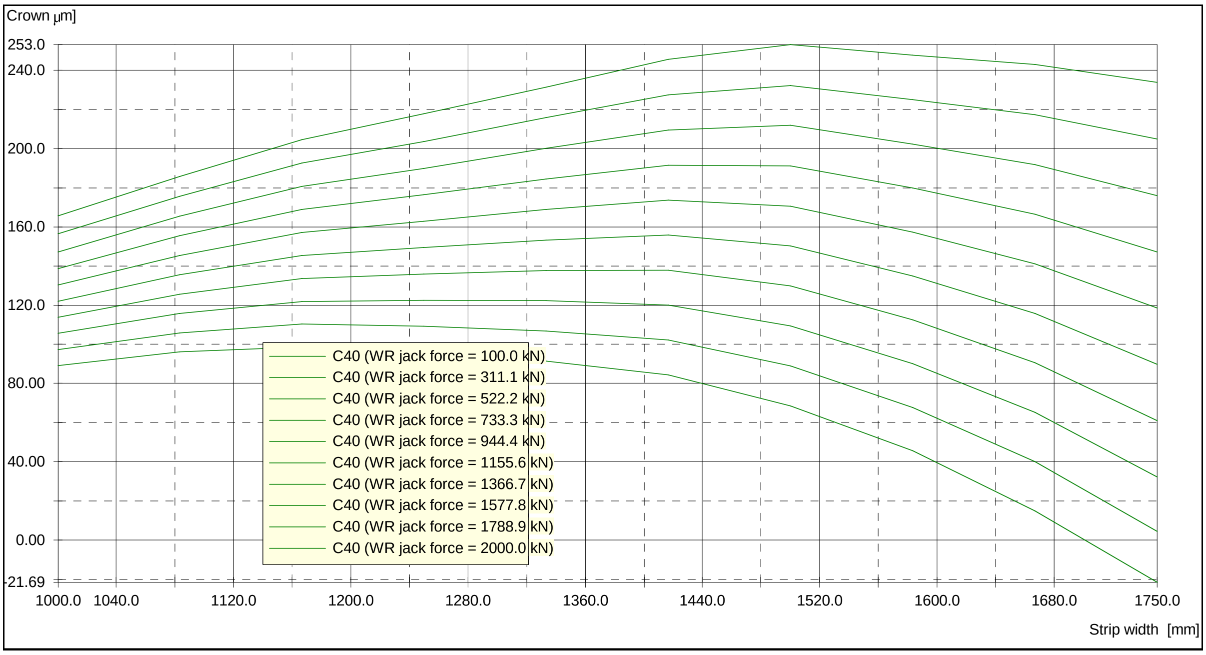


Figure 10: Strip crown versus strip width and WR jack force.

Strip profile curve can be decomposed into parabolic, cubic, quartic and higher polynomial parts.

$$tc - tx = C_1x + C_2x^2 + C_3x^3 + C_4x^4 + ..$$

where x - distance measured from centreline divided by half strip width (-1>x<+1),

tx - strip thickness in arbitrary coordinate x,

tc - strip thickness in centre.

Only one part of the calculated profile can be considered, finishing in the distance x from the strip edge. Then we get C_{2x}, C_{3x} and C_{4x} (x – distance from strip edge). It is very demonstrative to plot strip profile in C_2, C_4 coordinates (Figure 11). In this way strip profiles being reached by one or more actuators can be simply investigated.

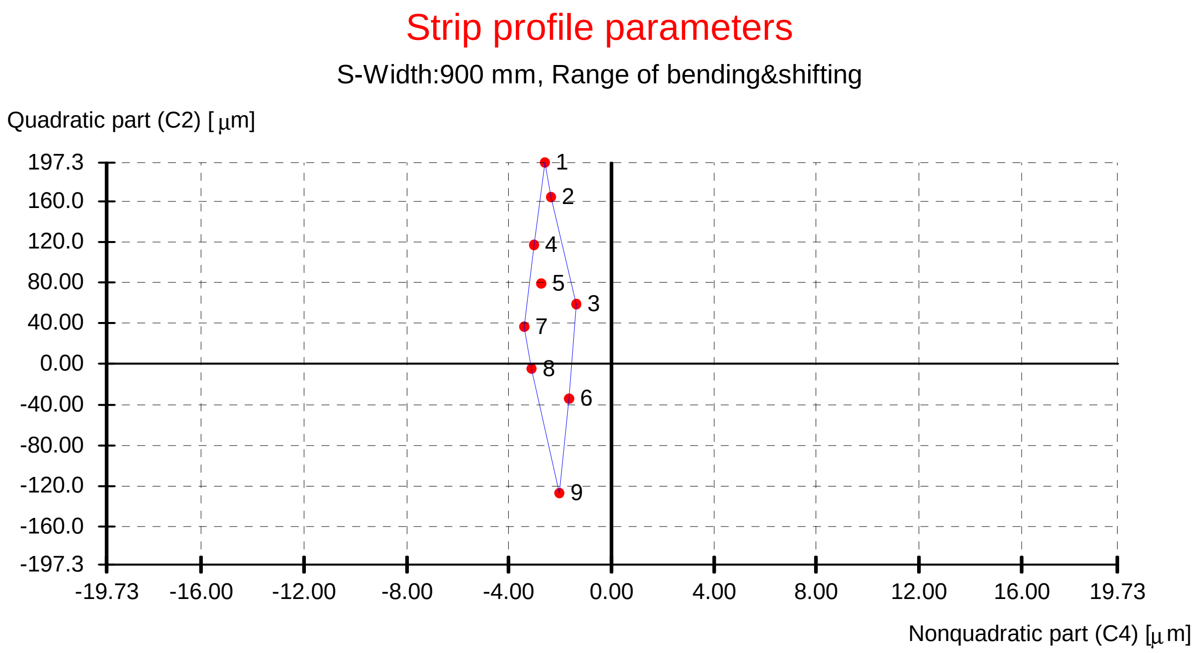


Figure 11: Range of actuators (bending and shifting) in space C2-C4.

The **crown sensitivity** (Figure 12) towards changes of various parameters is defined as:

$$\frac{\partial Cr_x}{\partial Par} = \frac{\Delta Cr_x}{\Delta Par}$$

where $\frac{\partial Cr_x}{\partial Par}$ .... partial derivative of crown,

. ΔCr_x .... difference of crown,

ΔPar .... difference of the parameter.

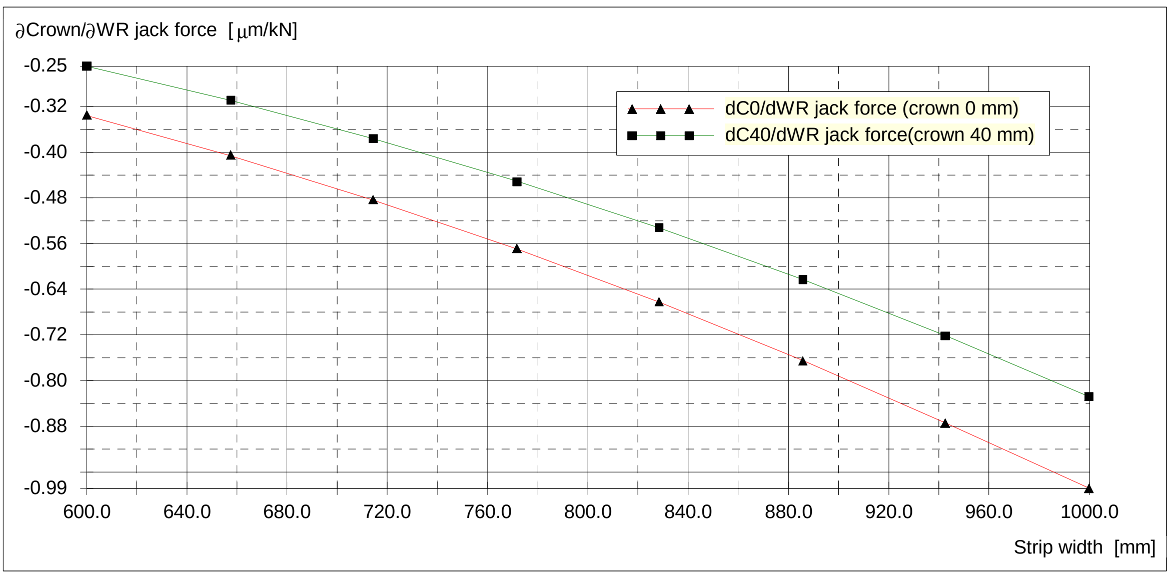


Figure 12: Strip crown sensitivity versus strip width.

6 CONCLUSION

Models for roll stack deformation and flatness control have been briefly described. Models are used in on-line and off-line versions. On-line version is suitable for control of bending forces and shifting, off-line version is intended for monitoring of existing Level 2, for parametric studies and for investigation of various parameters on rolling process.

On-line version is used in several mills for setup of bending forces controlling flatness of strips and sheets (Hot strip reversing mill, hot strip continuous mill, hot aluminium reversing mill). Of-line version supports technologists and helps them to optimize grinding of rolls, reducing danger of BuR spalling and other optimizing of rolling process.

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