ROLL PASS DESIGN METHODS FOR THREE- AND FOUR-ROLL ROLLING MILLS – COMPARISON AND ANALYSIS*

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Abstract
In bar and wire rod mills, rolling procedures featuring three- and four-roll technologies are state-of-the-art to produce high-quality long products. While a rolling model for the three-roll process including an equivalent pass method was already presented by the author, pass design methods are dealt with in the current work. The geometry of the rolled product and roll grooves are described mathematically using functional contours, allowing geometric-numerical methods to be used for manipulation and deformation simulation of the rolled product. For a given pass, the output section is constructed using these methods. Roll force, torque and rolling power are calculated using the mathematical rolling model presented before. Interstand tensions are discussed as influencing parameters on the force, torque and power demands, as well as on the section shape. A mathematical model for the influence of interstand tensions on lateral spread is incorporated in the model. To complete the pass design model, elastic mill stand feedback is considered in terms of a fixed elastic modulus for each rolling stand, the elastic feedback and therefore cross-sectional variation due to elastic mill spring being calculated iteratively from the roll force by application of the Gagemeter equation. The interaction of section height and width faults due to elastic mill spring and spread variations is analyzed in detail and the consequences for the roll pass design are shown.
Keywords: Pass Design;Four-Roll Process;Elastic Stand Feedback;Interstand Tensions.

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1 INTRODUCTION

The present paper focuses on roll pass design methods for rolling mills utilizing the three-roll process (3RP) and the four-roll process (4RP). The three-roll rolling process has been known for a few decades and has advanced to a well-established production technique when wire rod and bars shall be produced over a wide range of dimensions and materials in close tolerances. Its use of three instead of two rolls leads to an increase in elongation efficiency and a decrease of roll force.
For sizing purposes, the four-roll process (4RP) has gained industrial interest in the last year. Usually, it is combined with two passes in the two-roll process (2RP) to achieve high reductions, and 3 passes in the 4RP for sizing and close tolerances. In the following chapters, it will be shown how the pass designs can be constructed for these rolling processes.

In the current literature, a comparison between pass designs of the 2RP, 3RP and 4RP processes for similar purposes is still missing. The current paper aims at presenting a contribution to fill in this gap.

2 FUNDAMENTAL METHOD OF PASS DESIGN FOR TWO-ROLL PROCEDURES

Classically, in rolling of long products will full cross sections, the method of major groove-minor groove is applied. In a typical wire rod mill, an initial square billet of 140 mm square is reduced to a final cross section of 5.5 mm diameter.

The reduction of a round section to a smaller cross section takes place in main groove sequences. Each sequence consists of two passes. In the first pass of a sequence, the initial round section is deformed to an oval shape, which in the following pass is transformed into a smaller round section. The first step in obtaining the pass design is the design of the main groove section, i.e. the round sections.

The total elongation of a groove sequence is:

$$\lambda_{tot} = \frac{A_0}{A_f} \qquad (1)$$

The pass design is subdivided in main groove steps. Each step consists of two passes, one of which is an intermediate groove and one is a main groove. For the case of a round-oval pass design, the main grooves are round grooves, where the intermediate grooves are oval grooves. If N is the number of passes, the number of main groove steps is N/2. Therefore, it follows for the elongation of one main groove stepping (from round to round):

$$\lambda_{step} = \sqrt[\frac{N}{2}]{\lambda_{tot}} \qquad (2)$$

The elongation sequence acc. to Eq. 2 should be stepped degressively, to avoid flat oval grooves in the last passes where relation of section size to roll diameter may become ineffective.
The main groove method as described here is the basis for the two-roll pass design. However, for three- and four-roll pass designs, different methods have to be used, which are shown in the following sections.

In the computer model which was developed for pass design of a variety of rolling processes, all geometries are treated as polygonal contours. This led to the circumstance that any geometrical shape, including unsymmetrical imperfections resulting from the rolling process can be accounted for.

3 CALCULATION OF LATERAL SPREAD FOR FLAT PASSES IN THE 3RP AND 4RP

For the 2RP, a lot of empirical spread models are available. There are models due to Wusatowski, Roux, Marini, Sander, only to mention a few. In a paper by Mauk [1], a few of these spread models are compared to one another and to measured values for the 2RP.

It would be a nearly impossible approach to find new spread models for the 3RP and 4RP in the same detailed description that is available for the 2RP. We can also assume that most of the influencing parameters on spread (geometry, roll diameter, friction) will influence the 3RP and 4RP in a similar manner as in the 2RP. Because of this circumstance, the spread calculation for the 2RP will be used for the 3RP and 4RP with a suitable transfer approach. This approach is firstly described for the 3RP in the next paragraphs.

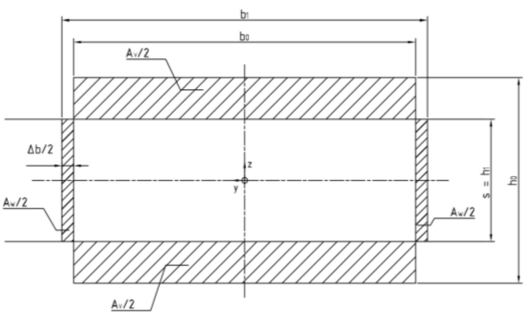

Figure 1. Spread characteristic in a two-roll pass

Figure 1 shows the geometrical features of a flat pass with lateral spread in the 2RP. A part of the cross-section of the entry rectangular contour is displaced by the rolls. We call this area the displaced area A_V. This displaced area will flow preferentially in the longitudinal direction, but a certain lateral material flow will be present – that is the lateral spread. A part of the displaced area will come back into appearance – we call this area the reappearing area A_W. A part of the reappearing area will be again displaced in the following pass. Therefore we can define the elongation efficiency in the following way:

$$f_S = 1 - \frac{A_W}{A_V} \qquad (3)$$

A typical section rolling pass will have an elongation efficiency of 60 % - 90 %, depending on the spread influencing parameters like roll diameter, temperature and interstand tensions. If a weak elongation efficiency of less than 60 % is discovered, the pass design should be optimized.

The 3RP and 4RP do have a better elongation efficiency than the 2RP, since when we involve more rolls at the section circumference to achieve a deformation, we inhibit the lateral spread up to a certain extent because the material has less directions in the cross-sections were it can direct its material flow into.

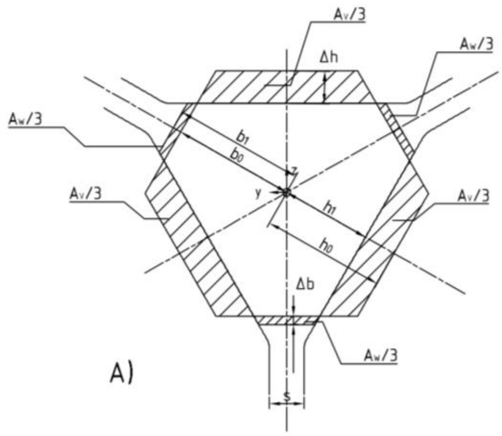

Figure 2. Spread Characteristics in a three-roll pass.

To quantify this effect, we look at a 3RP flat pass with a similar cross-sectional reduction, Figure 2. Here, the overall reduction is distributed on three rolls instead of two, therefore the reduction per roll is lower than in the 2RP, and the spread in each of the roll gaps will be lower.

We address this circumstance by formulating the spread difference in a 2RP flat pass not in terms of the overall height reduction, but in terms of the height reduction per roll.

Generally, this leads to a correction factor for the spread of 2/3 in the 3RP, compared to the 2RP. A similar consideration can be done for the 4RP, here the spread correction factor will be ½ in reference to the 2RP.

4 EQUIVALENT PASS METHOD FOR THE THREE- AND FOUR-ROLL PROCESSES

After the rolling model, including the calculation of lateral spread has been established for flat passes in the three- and four-roll rolling processes, an equivalent pass method is needed to enable the calculation of non-flat roll and initial section contours.
The aim is the calculation of an equivalent flat pass, at which the lateral spread of the section pass can be calculated.

Here, a certain reference is made to Lendl's equivalence method for the 2RP, which is logically adopted for the three- and four-roll processes.
Figure 3 shows equivalent sections for a non-flat pass in the three-roll method.

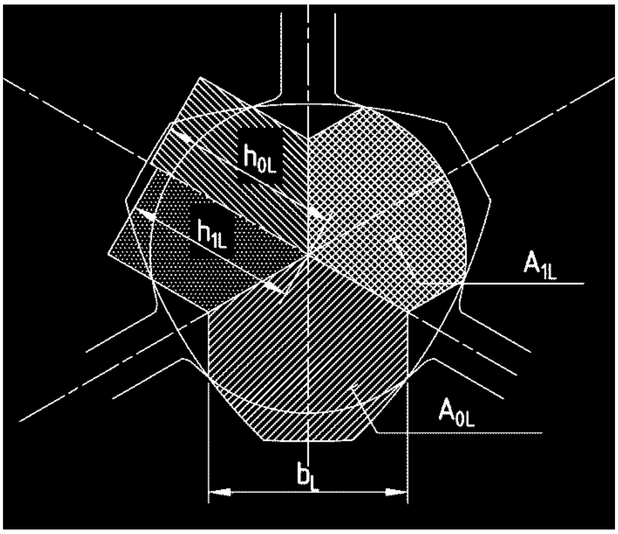

Figure 3. Characteristic Data for the equivalent pass method in the 3RP.

To apply the procedure, firstly the roll contour and the initial section contour are plotted on top of each other. Then, the cutpoints of the two contours are searched.

Typically, two cutpoints on each of the roll contours are found. This means, 6 total cutpoints are found for the 3RP and 8 for the 4RP. Figure 4 shows the equivalent areas for the 4RP.

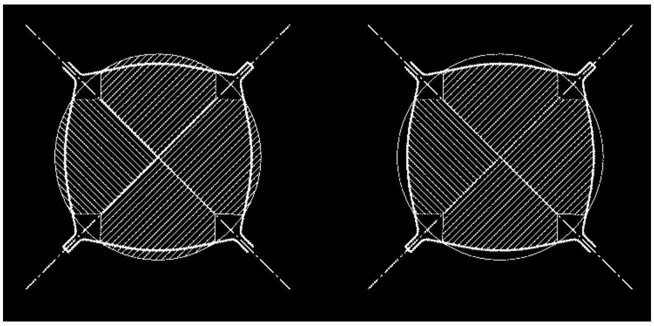

Figure 4. Equivalent areas of a four-roll pass. Left: initial area A_{0L}, right: roll contour area A_{1L}

Now, the equivalent areas A_{0L} and A_{1L} are constructed as shown in Figures 3 and 4. These have now to be compared to a pentagon area with 120 degrees base angle (3RP) or 90 degrees base angle (4RP) to find the equivalent entry and exit heights of the corresponding flat pass.

5 TYPICAL ROLL GEOMETRIES FOR THE THREE-ROLL PROCESS

To form a round section in close tolerances and to be able to cope with changing spreading behavior and elastic deformations in the rolling process, different groove geometries are used. The simplest one is the flat groove, which is defined by an inner diameter and a roll gap, Figure 5.

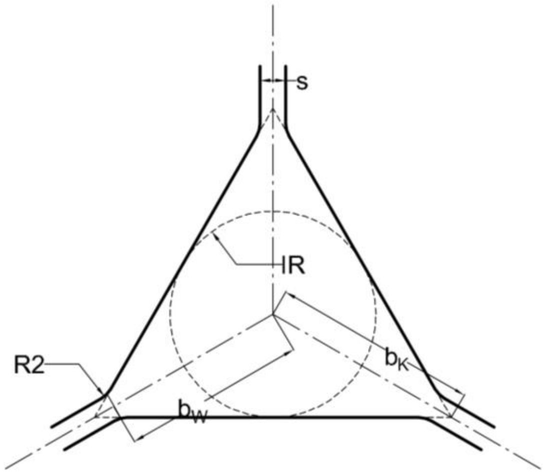

Figure 5. Flat Groove for the 3RP.

A special form of this groove is the crowned flat groove, Figure 6. This geometry is used to optimize the biting behavior of the initial section and to prevent the section from rotating while it is deformed in the roll gap.

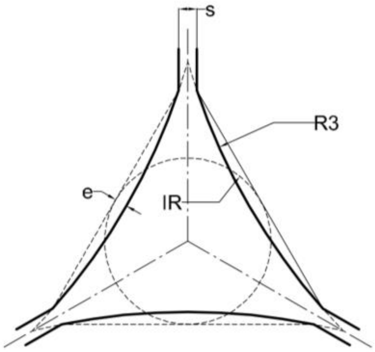

Figure 6. Crowned Flat Groove for the 3RP.

The round and oval grooves can be further subdivided in different categories. Firstly, concentric and eccentric grooves can be distinguished from each other. At the concentric groove types, the main radius R_1 is always $R_1 = d/2$, and therefore the inner circle of the groove and the groove radius share the same center point.

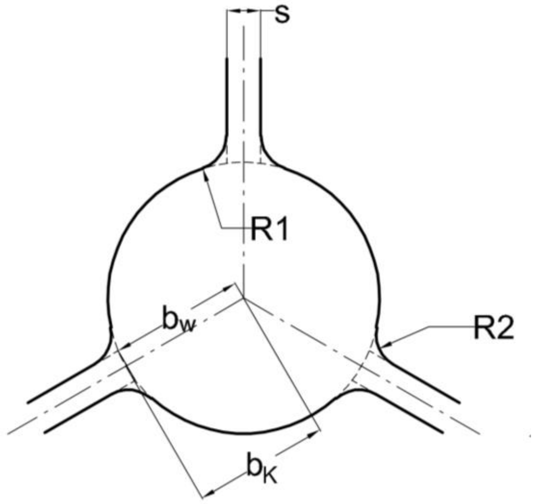

Figure 7. Concentric groove for the 3RP.

In eccentric grooves, this is not the case; the main radius is usually R1 >> d/2. With this geometry, simple oval groove types can be constructed for pre-sections without the need of tangentially opened groove geometries.

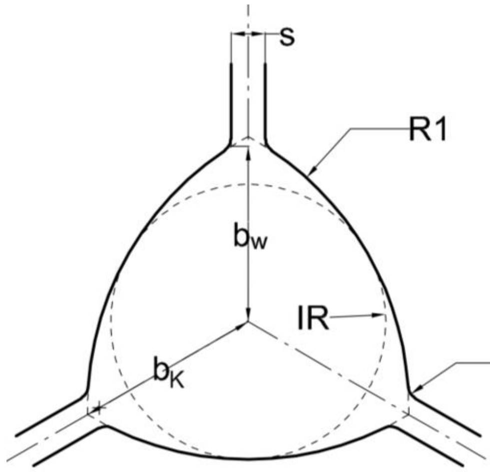

Figure 8. Eccentric groove for the 3RP.

Secondly, 3RP groove geometries are distinguished by the condition if they are opened tangentially.

Tangentially opened grooves are used to provide some flexibility for close tailored grooves for spreading variations of the rolled material. However, they can also be used to construct grooves for more oval-shaped pre-sections.

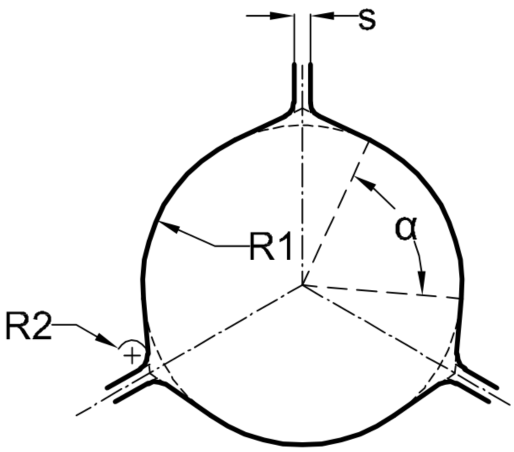

Figure 9. Tangentially opened groove for the 3RP.

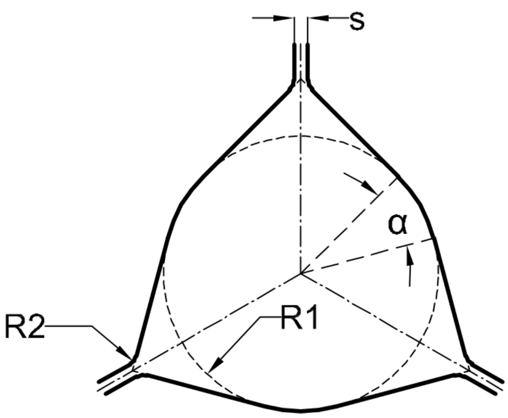

Figure 10. Tangentially opened groove for the 3RP with a smaller angle to form a preliminary section.

After all, we can treat eccentric grooves and tangential grooves as two different philosophies for the three-roll pass design.

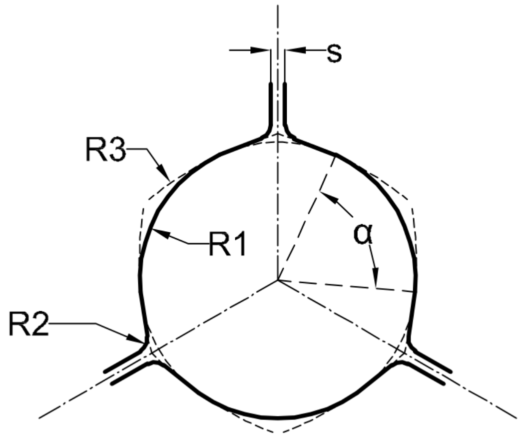

Figure 11. Tangentially opened double-radius finishing groove for the 3RP.

6 TYPICAL ROLL GEOMETRIES FOR THE FOUR-ROLL PROCESS

In the four-roll rolling process, the groove geometries to be used can also be eccentric, concentric, opened and non-opened. Figure 12 shows an opened, non-eccentric groove with an opening angle of 60 degrees.

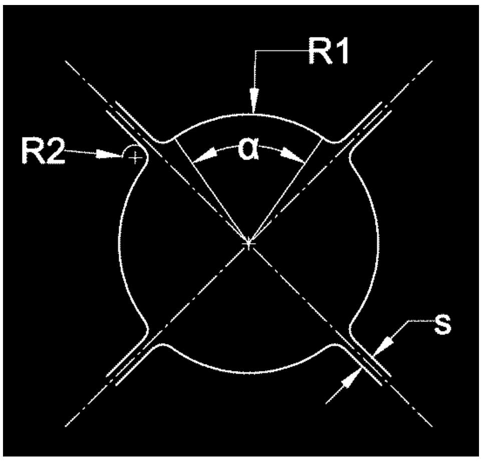

Figure 12. Single-radius round groove for the 4RP.

This groove type is generally used as a finishing groove for a four-roll pass design. An eccentric opened groove for a pre-section is given in Figure 13.

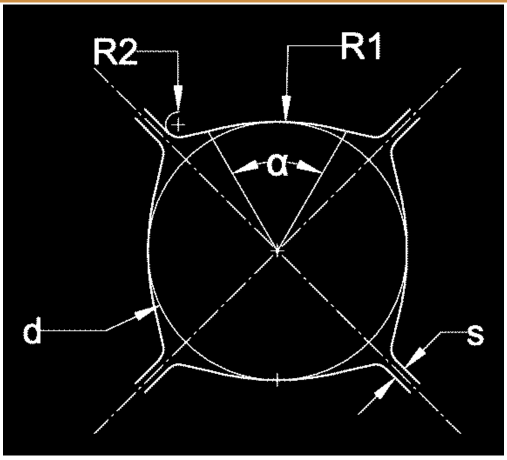

Figure 13. Eccentric groove for the 4RP (first pass).

7 PASS DESIGN FOR A THREE-ROLL MILL

We will discuss a six-stand arrangement for a three-roll rolling mill with roll diameters of d_b = 360 mm at the roll barrel. An initial section of d_0 = 28 mm shall be reduced to a finished diameter of d = 16 mm in six passes.

The first pass design method is the so-called tangential pass design. In this method, tangentially opened round grooves are used throughout the pass design. Typically, in the first pass an opening angle of approx. 30 degrees is used to provide a good contact condition for the initial round section. Because of these geometrical conditions, the pass reduction in the first pass is generally in the order of magnitude of 15 percent.

Table 1. Pass Design Result for 28 mm – 15 mm in the Tangential Three-Roll Method

Pass	Groove Diam.	Groove Radius	Opening Angle	Draft %
1	23.89	12.92	30°	14.8
2	19.71	10.82	30°	29.8
3	17.43	9.38	35°	24.8
4	15.89	8.41	40°	19.5
5	15.11	7.80	50°	13.8
6	15.00	7.50	75°	6.9

Table 1 shows the pass design results for the tangential design. The general philosophy is to combine high reductions in the first passes with low reduction in the later passes to achieve a good deformation from surface to core of the material and close tolerances with low roll forces in the later passes.
The highest reduction is encountered in the second pass, where the section shape is very triangular. This is shown in Figure 14 for the second pass.

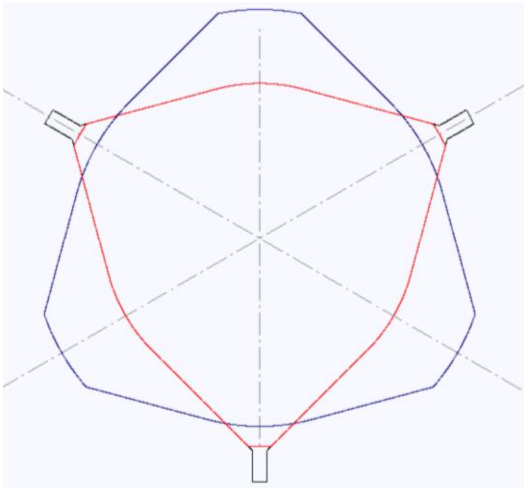

Figure 14. Second pass of table 1 with the highest reduction (29.8%) and triangular section shapes. Blue: entry section; red: exit section

7 PASS DESIGN FOR A FOUR-ROLL SIZING MILL

Four-Roll rolling mills are used to size an entry section to a smaller final section in close tolerances. To achieve this, usually two passes in the two-roll process with high reductions are combined with two or three passes in the four-roll process [4,5]. The philosophy behind this is to achieve a certain smoothing of cross-sectional faults, while only negligible new faults are introduced.
Figure 15 shows the geometrical situations for a given four-roll groove with a high eccentricity (R1 = d) and the biggest possible entry section that does not overfill the groove.

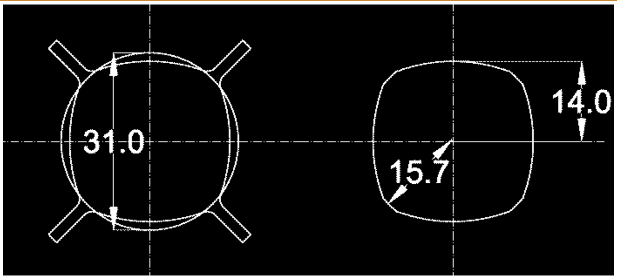

Figure 15. 4RP intermediate groove with initial 31 mm round and output section. Reduction: 9.8%, elongation efficiency 95.6 %

Generally, the elongation efficiency for the 4RP is very good because the total deformation is distributed on four rolls.

We shall now discuss a typical rolling procedure on a combined 2RP and 4RP rolling block with 5 stands in total.

The stand data is given in the following table.

Table 2. Technical parameters for a combined 2RP and 4RP sizing block

Pass	Method	Roll Diameter
1	2RP	230
2	2RP	230
3	4RP	250
4	4RP	250
5	4RP	250

An initial section of d = 35 mm diameter is fed into the rolling block. It is reduced in the first two passes to a section of d = 27 mm.
This section is further processed in the three remaining four-roll passes to a final round of d = 24 mm.
Figure 16 shows the calculated section geometries for the five passes.

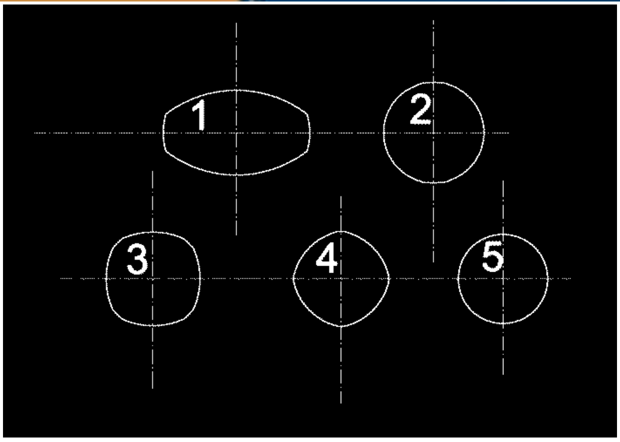

Figure 16. Calculated cross sections for the rolling procedure in the combined 2RP and 4RP rolling block.

Table 2. Deformation characteristics of the combined 2RP-4RP rolling block

Pass	Area [mm²]	Reduction	f_S
1	720.6	25.1 %	82 %
2	574.1	20.3 %	73 %
3	535.2	6.7 %	96 %
4	475.7	11.1 %	97 %
5	452.9	4.8 %	98 %

8 CALCULATION OF ROLL FORCE AND TORQUE

As the rolling force and torque are important process parameters, a reliable method for its calculation has to be applied.
For the present analysis, a rolling model for the 3-roll rolling process which has been published before is used. Here, the well-known slab method for two-roll rolling is extended to the three-roll geometry. It has been found that a general form of von Karman's differential equation can be stated, that is valid for the three and four-roll methods [2]:

$$\frac{d\left(\sigma_x A\right)}{dx} = b_C \cdot \left(\sigma_N \tan\alpha \pm \tau_f\right) \qquad (4)$$

In Eqn. (4), b_C is the contact width (length of the roll barrel which is in contact with the rolled bar, see [2]), A is the local cross section and σ_N, σ_x and τ_f are the horizontal, normal and frictional shear stresses, respectively.

For each of the different processes, a suitable force decomposition in the yz-plane has to be added to the theory to account for the different roll inclination angles which are characteristic for the corresponding rolling process, see [2] for an example of the 3RP.
In this regard, it should be emphasized that the yield criterion is crucial for the characteristic rolling theory of the different processes. A plane strain assumption cannot be made for the three- and four-roll rolling processes.

9 INFLUENCE OF INTERSTAND TENSIONS AND ELASTIC FEEDBACK

Interstand tensions influence the spread behavior, but also have influences on the calculated roll force and torque quantities.
Tension influences could be introduced in the spread calculation directly, but a different approach is used in the present analysis to maintain flexibility for different spread calculation models.
The total deformation (true strain) of a pass is formulated as the superposition of a non-stress influenced part φ_{l0} and a tension-influenced part $\Delta\varphi_{l\sigma}$. The total deformation is therefore

$$\varphi_l = \varphi_{l0} + \Delta\varphi_{l\sigma} \quad (5)$$

For $\Delta\varphi_{l\sigma}$, a polynomial approach is used. We may write according to [3]:

$$\Delta\varphi_{l\sigma} = k_1\left(\frac{\sigma_0}{k_{fm}}\right)^2 + k_2\left(\frac{\sigma_0}{k_{fm}}\right) + k_3\left(\frac{\sigma_1}{k_{fm}}\right) \quad (6)$$

where the coefficients k_1, k_2, k_3 are functions of geometric properties of the roll gap:

$$k_i = m_{1i}\frac{\Delta h}{h_0} + m_{2i}\frac{b_0}{h_0} + m_{3i}\frac{A_d}{A_m}\ ;\ i = 1...3 \quad (7)$$

m_{ij} in Eqn. (6) are regression coefficients. The model as proposed here and in [3] can be adapted to any measured values of tension influence on lateral spread.

The elastic deformation of the rolling mill equipment is described by means of the gagemeter equation:

$$s = s_0 + \frac{F}{C_G} \quad (8)$$

The effective roll gap s is described as a function of the setup roll gap s_0 (without force), the roll force F and the rolling stand rigidity constant C_G. This calculation has to be repeated iteratively, because the calculation of the roll force and the elastic feedback are dependent on one another.

Figure 17 shows the effects of elastic stand feedback exemplarily for a 3RP pass. A round section is fed into a triangular roll groove. Disregarding elastic rolling stand deformations, the exit height h_1 and exit width b_1 appears. Under the effect of elastic deformations, a greater height h_1'>h_1, but a lower width b_1'>b_1 appears.

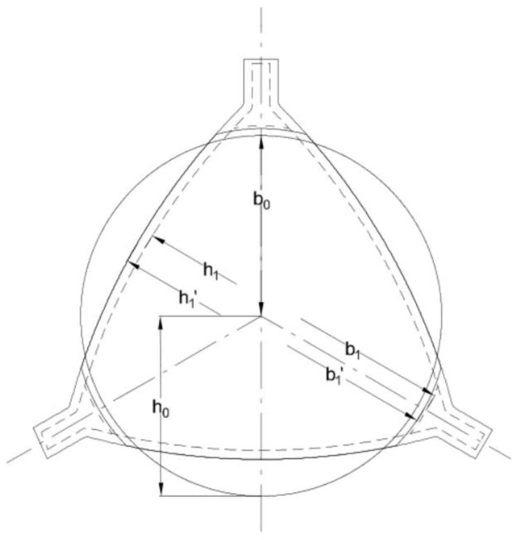

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Figure 17. Effects of elastic rolling stand feedback. Dotted lines: original roll geometry; solid lines: roll geometry under elastic deformations. h_1: original exit section height; h_1': exit section height under elastic deformation; b_1: original exit section width; b_1': exit section width under elastic deformation.

The following example shows the influence of interstand tensions which arise during rolling in the two mill configurations which were exemplified by tables 1 and 2.

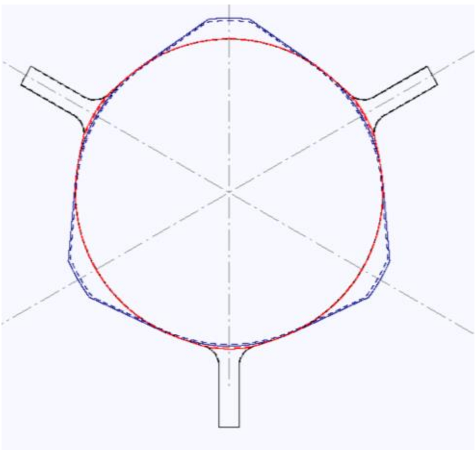

Figure 18. Calculated effects of elastic rolling stand feedback and tensions for the pass design presented in table 1. Dotted lines: original roll geometry; solid lines: roll geometry under elastic deformations.

Figure 18 shows the calculated section shapes (blue: entry section, red: exit section) for the last pass of the three-roll rolling mill. The dashed lines correspond to the tension- and feedback-free case, were the solid lines correspond to the more realistic case where interstand tensions of 10% of the flow stress were taken into account. We can see, that there is only little difference in the final section because of the low designed reduction of 6.9 % (see table 1) of the respective pass.
This is also seen for the 4RP pass design. The final pass is shown in Figure 19.

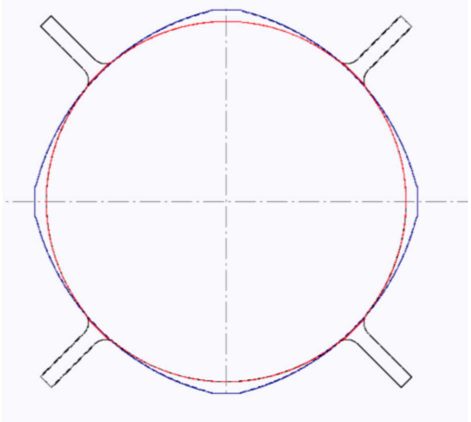

Figure 19. Calculated effects of elastic rolling stand feedback and tensions for the pass design presented in table 2.

Where small deviations can be seen at Figure 16 for the 3RP, for the 4RP we don't see any tension and feedback effects at all in Figure 17. This is due to the fact that the pass reductions are effectively reduced when the rolling process is changed from the 2RP to the 4RP.

10 RESULTS AND DISCUSSION

The pass design results presented in sections 6 and 7 indicate, that a general pass design method for both three- and four roll rolling process could follow similar principles. In both cases, from a round entry section, a more triangular (3RP) or rectangular (4RP) section is created in the first pass, which is then reduced with a strong degressive elongation distribution to the final round section. This pass design method has the advantage that it can be used for both high and low reduction sequences.

Generally, we should note that each rolling pass is fed with an entry section coming from previous passes which introduce more or less high deviations form the ideal desired shapes because of the elastic behavior of the rolling stands. As a degressive pass design characteristic is used throughout the mill in most of the practical cases, the later passes will also "smoothen" the present sectional deviations. It is the goal for a good pass design to strengthen the smoothening effect, while the introduction of new section deviations is prevented.

This can be achieved by a strongly degressive pass design, so that by only low reductions in the last passes, also the rolling forces will be low, leading to lower elastic feedback and in turn to lower interstand tensions. This is the “sizing approach” which was emphasized by the present paper.

Based on the equivalent pass method presented by the author for the 3RP [2], other authors used a similar approach for the 4RP. The author of the present paper constructed a computer solution for the automated calculation of pass designs for all 2RP, 3RP and 4RP processes for wire rod and bars.

11 CONCLUSION

We may conclude that modern rolling processes like the 3RP and 4RP provide better possibilities for section homogenization throughout a rolled strand of material, but specialized pass designs have to be worked out for these processes, combining high reductions in the first with low reductions in the last passes.

Acknowledgments

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Special thanks are owed to the memory of my academic teacher Prof. Dr. Paul Josef Mauk. His early death left a gap that cannot be filled.

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