Roll Pass Design for Improved Flexibility and Quality in Wire Rod Rolling

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Doctoral Thesis

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Stockholm November 2004
Abstract

The thesis treats roll pass design in wire rod rolling of stainless steel for sequences and series built up by two-symmetrical grooves. It is focused on predicting rolling flexibility, also called working range, as well as product quality. For analysing the flexibility a computer program has been developed. The minimum and maximum roll gap and corresponding bar areas for series of grooves including “oval”, “round”, “false round”, “square” and “diamond” shapes are calculated. Six pass designs used in Swedish mills are analysed. Full-scale rolling is compared with laboratory experiments for the square–oval and false round (round)–oval series. The false round–oval series offers the largest working range and that the flexibility is smaller for pass sequences designed for high reductions. The false round–oval series are also acknowledged as a series for high quality steels and are usually better than the square–oval series having a tendency for defect formation. The thesis also includes high-speed rolling of wire rod in blocks. Here interstand tensions are utilised in order to keep the process stable. For obtaining the required dimensional tolerances of the product they are kept as low as possible. However interstand tensions could be used in order to increase the working range and move the product range towards smaller wire cross sections. For analysing this possibility, a narrow spread technology is utilised. At present time a practical problem is referred to the fixed gearings in the common blocks, which require a certain and given level of interstand tensions and corresponding reductions. This problem can however be solved by means of new block design and modern process control technology. Roll stands can be separately driven and controlled at very high speeds. Thus the eight stand blocks can be subdivided into four plus four passes blocks with a cooling line between enabling also higher productivity without violating the product quality because defect formations caused by a too high rolling temperature. The true working range of a series for a specific steel grade is however not only dependent on the possible spectrum of wire dimensions that can be obtained but might also depend on its ability to decrease or eliminate defects such as surface cracks. Thus, the behaviour of artificial V-shaped cracks in the longitudinal direction has been investigated and compared for the square–oval and false round (round)–oval series mentioned above. In agreement with other research works it was established that efficient rolling conditions for reducing the cracks are obtained when the cracks open up at the same time as their depth is reduced. If the V-shaped crack is closed by contact between its oxidized side surfaces the rolling schedule is not optimal for getting a high quality product. A deeper understanding of the experimental results was obtained by means of an FE-analysis.

Keywords: Wire rod; Roll pass design; Working range; Productivity; Swedish wire rod mills; Interstand tension; Surface cracks and defects
Acknowledgments

I wish to thank my supervisors Professor Ulf Ståhlberg, Royal Institute of Technology, and Assistant Professor Sven-Erik Lundberg, Örebro University, for many discussions, good ideas, help and patience. Thanks are due to the Swedish Steel Producers' Association (Jernkontoret) research committee 3277. Henrik Överstam M.Sc., Örebro University, is acknowledged for his assistance with the FE-simulations. Special thanks to Ms Therése Gustafsson for all her help with the CAD-drawings connected to the pass design.

Finally, my thanks to Fagersta Stainless AB and my superiors Managing director Jan Pieters, MBA, General Manager for production Conny Fredriksson, M.Sc. and Manager for wire rod mill Mr Nils Degerman for their support and persistence in letting me penetrate more deeply into this work.
Dissertation

This dissertation contains a summary and the following papers:


Paper C  Conny Eriksson, Surface Cracks in Wire Rod Rolling, Accepted in April 2004 for publication in Steel Research International.


Paper E  Sven-Erik Lundberg and Conny Eriksson, Ultra-high Speed Rolling of Stainless Steel Wire Rod by means of Interstand Tensions, Accepted with minor alteration in October 2004 for publication in Berg- und Hüttenmännische Monatshefte.
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<td>References</td>
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Appendix Paper A-E with Supplements

Enclosed Announcement for Defence of Dissertation with Abstract

Figures with symbol • means that a figure of better quality can be found in the supplements for the appended papers.
1. Background

This chapter presents a short historical background to the development of the scientific field named “roll pass design”. It focuses on Sweden and the basic conditions for this country, such as good access to high-grade ore, which motivated a rapid industrial evolution.

In the late 19th century, the industrialisation started in England and was spread over Europe during the next century. Compared to other countries this evolution started relatively late in Sweden. An important determination, for accelerating the building of an industrialised society was the introduction of free trade rights in 1864, including the permission for everybody to start private businesses and limited companies [1].

In 1853-54 it was decided that trunk lines should be built at the expense of the government while private companies should be responsible for the local lines. In 1892 a railroad from the rich iron ore mines in the far north of Sweden to the eastern harbour of Luleå was opened and in 1903 a new line to western coast of Narvik was taken in operation [2]. These lines made it possible to explore the mines and already in 1890 the enterprise Luossavaara-Kiirunavaara AB (LKAB) was founded. The location of the iron ore was known already in the 17th century, but due to the lack of metallurgical processes to take care of its high content of phosphorous, they had not been exploited yet [1, 2]. The expansion of railways in this sparsely populated country required efficient manufacturing technology to roll the rails and other complicated sections. Thus new methods for roll pass design were developed rapidly.

The first telephone line was opened in 1853 in the close area of Stockholm. Ericsson began the production of telephones in 1880. No single invention has enhanced the wire rod production, which is the topic for this thesis, as much as the breakthrough of the telegraph and later the telephone [2].

In 1883 the electrical power company ASEA, today ABB was founded on patents to solve the problems to transmit electrical power over long distances, by means of three-phase AC. In the beginning of 20th century the Swedish State got the right by law to exploit its big rivers, basically in the northern part of Sweden [2], and here the generation of hydropower started 1910-15 and in the southern already 1906-1910 [2]. The first time electrical power was utilised for driving a Swedish rolling mill was in the year of 1894 [3].

The demand for steel increased rapidly in the late 19th century due to the building of the new infrastructure such as roads, railways, bridges, telecommunication networks and machines for the industrialisation itself. A few
large plants replaced a large number of small old mills at the same time as new ones were founded and a new structure of the Swedish steel industry started to take shape [2].

In the late 19th century, the demand on the rolling process to increase its productivity became of utmost importance due to the breakthrough of the Bessemer process, which provided a dramatically higher steel making capacity than the older finery hearths. As a consequence, the productivity in the bar and wire rod mills improved drastically. During the 20th century the exit rolling speed for wire rod in round 5.60 mm increased from “hand rolled” wire of 5-6 m/s (18-22 km/h) to a “state-of-art” 140 m/s (500 km/h) [4, 5]. The theoretical capacity increased from 4 t/h to 94 t/h. This became possible thanks to the invention of the electrical drive, the introduction of roller bearings, mechanised rolling, the wire rod blocks, the increase of coil weight from about 200 kg up to 2,5 t and the digital control systems [6].

An important change in iron and steel making organisations and in the working processes started in the late 1980th. In cooperation between the trade unions and the employed staff, big improvements were obtained. In the organisation drastic measures were taken for promoting work efficiency [7]. The traditionally well-educated Swedish work force now takes more responsibility for the operation of the mill and the product quality. The hierarchic industrial structure no longer exists [8]. Many companies have turned over to flat organisations with a high degree of responsibility delegation.
2. Introduction

In bar and wire rod mills, which is the topic of the thesis it is normal to use rolls furnished with grooves. Common groove sequences in intermediate mills are “square–oval” and “false round (round)–oval”. It is also widespread to use “diamond–square”, “diamond–diamond” and “box groove” sequences upstream in the roughing mill. This work focuses on productivity and working range of the rolling series, which are built up by sequences consisting of two-symmetrical cross-sections, and on product quality.

To improve the productivity, many investments are focused on minimizing the downtime in the mills. The effectiveness has been enhanced by reducing the time and need for changing rolls when new final dimensions and new steel grades and shapes are to be manufactured. This has been achieved by improving the working range, also named flexibility of the series. Improved flexibility is reached when a large amount of different steel grades, with different shapes and dimensions can by rolled with a minimum change of the rolling schedule. Every steel grade is characterized by its specific way of material flow, such as different spread, when passing through the roll gaps. Also the start-up time and time waiting for correct rolling temperature, depending on the actual steel grade, has been decreased. However, different heating cycles still cause too high downtimes when a wide range of grades is to be rolled. In order to meet the market demands of today, which includes smaller lots and numerous kinds of steels, it has become a necessity that the modern wire rod mills show a high degree of flexibility. A wire rod mill for stainless steel must be able to roll mixed combinations of all types of ferritic, austenitic, martensitic, duplex and other types of high alloy stainless steels, heat resistant and nickel base alloys in an economical way. To clarify more into detail, all these materials need different heating and rolling temperatures, inline annealing, and various handling equipments. Many rolling mills work with the OEE-philosophy (Overall Equipment Effectiveness) and register all downtimes eased by for example gap time loss, speed losses, cobbles, non-conforming products and quality deviations [9].

A high yield and adequate product quality is of utmost important to reduce the costs. Some stainless steel alloys are extremely expensive, with a billet cost of €4000–9000 per ton and even more, i.e. one single billet can have a value of up to €25000. Product quality has become increasingly important. For many applications of wire rod in stainless steel, it is impossible to accept surfaces with any marks, scratches, shells, cracks, overfills or oxide particles on the surface. Eddy current equipment in-line is used for detecting surface defects. The market demands on closer tolerances have also increased. Many rolling mills of today have on-line gauge measurement systems [10] and on-line gap adjusting...
procedures. These systems make it possible to be on dimension on the first rolled bar, to have full control of the rolling and to eliminate the need for rolling trial bars.

In wire rod rolling, usually twenty-five to thirty passes are taken in a continuous or a semi-continuous line. Two examples of modern wire rod mills, one fully continuous mill and one mill with reversing roughing mill are shown in Figure 1a and b respectively.

Figure 1. An example showing layouts a) for a fully continuous wire rod mill and b) for a wire rod mill with a reversing roughing mill and a continuous intermediate and finishing line.

Figure 2 shows a typical roll pass design for the two kinds of mills. Square billets of 140 mm and 150 mm a length of 12 m and typical 2 t weights are reduced in thirty passes to round 5.60 mm. To change dimensions a large part of the grooves and stands must be changed.
Figure 2. An example on pass sequences showing different roll pass design in roughing, intermediate and finish rolling for mills shown in Figure 1 a. Sequences in a fully continuous wire rod mill b. Sequences in a wire rod mill with reversing roughing. The horizontal lines show the stand and roll sizes.
3. **General Requirements on Modern Wire Rod Rolling**

The productivity and utility in the mills are dependent on the downtime in the mill, caused by the mill layout and product mix. In modern mills, the OEE-philosophy mentioned above is followed. The yield from billets to the final products is registered in all steps and the tracking of the material to follow up all time losses is excellent. The losses related to the theoretical production capacity are shown in **Figure 3** for two kinds of wire production, diverse production of special products and for volume production. The nomenclatures within the figures are made clear from the figure caption.

![Production Capacity for a Wire Rod Mill for Special Products](image)

![Production Capacity for a Wire Rod Mill for Volume Products](image)

**Figure 3.** An example on comparison of production capacity in a special steel mill with diversified product mix and a mill with an optimised product mix. $E$ stands for mill efficiency, $U$ for mill utility and $Y$ for product yield.
The theoretical production capacity is obtained in a mill without any losses or 100 % utility, 100 % efficiency and 100 % yield. If the theoretical production capacity is 100 kt/y and the OEE level is 50 % the mill will produce “only” 50 kt/y. The OEE are expressed in Eq (1):

\[
\text{OEE} = \text{Utility} \times \text{Efficiency} \times \text{Yield} \quad [\%]
\]  

(1)

The first factor is the roll utility or available operating time related to the planned production time or shift time. The second factor is the mill efficiency the running time related to the available operating time. Finally the third is the mill yield or time to produce a value-enhanced product related to the running time. The relations are shown in Figure 4 and in Eq. 2-4.

![Sources of Losses in a Wire Rod Production](image)

**Figure 4.** Losses in time in a wire rod mill related to planned production time or shift time.

\[
\text{Utility} = \frac{\text{Available operating time}}{\text{Planned production time}} \quad [\%]
\]  

(2)

\[
\text{Efficiency} = \frac{\text{Running time}}{\text{Available operating time}} \quad [\%]
\]  

(3)

\[
\text{Yield} = \frac{\text{Accepted coils weight}}{\text{Billets weight}} \quad [\%]
\]  

(4)
The OEE for a rolling mill can in worst case be as low as 20%. In a state-of-art mill with a well-optimised product mix, about 80% can be a good figure. Wire rod mills usually have lower OEE than strip mills because of the higher downtime for roll- and stand changing and groove and guide adjustments when shifting products. For all losses it is possible to calculate the “poor quality cost” of the mill, which is defined in Eq. (5).

Poor quality cost = Inspection + Internal faults + External faults [SEK] (5)

The “poor quality cost” can range from 10% for a high performance mill, up to 30% for a wire rod mill with more complicated production mixture. In some mills poor quality cost in the area of 9-16% of the business’ turnover, has been registered.

The main costs are due to “Inspection and testing” the product quality, and time and resources are spent on “Internal faults”. “External faults” are disturbing the market and the customers with bad quality. Usually it is fairly difficult to calculate those costs. The cost for rejections and claims from the customers are possible to calculate, but it is more or less impossible to estimate the cost for bad reputation on the market [11].

In a modern wire rod or bar mill the main focus are on productivity and quality. High utility, efficiency and yield give high productivity. But high productivity itself is not the only way to successes. The business must also be efficient on the market place. The products must give the customer added values. The customer must find the quality worth to pay for. Shortly said, the company must: “Do the right things in the right way” [12–14].
4. **Productivity**

A wire rod mill can be combined with a bar mill by means of a cooling bed outlet before the wire rod line. When rolls are changed in the wire rod block, the upstream mill produces bars in order to reduce the total downtime for the mill. The latest technology is to introduce “sizing mills” where the final shaping is done in three to five passes, by means of low reductions. In these kinds of finishing mills it is common to utilize modern electrical control concepts, which makes it possible to run the finisher at different reductions, and use a single family rolling philosophy upstream in the mill, thus reducing the resetting time.

In a mill, rolling a wide range of steel grades, downtime for waiting for the correct heating temperature when changing steel type, is an important restriction in the productivity. For example ferritic stainless steels need a lower heating temperature than austenitic stainless steels. Some special stainless steels and nickel base alloys need odd temperatures and some alloys have very narrow temperature ranges for rolling, due to poor ductility. One way to reduce the downtime for this reason is to have two or more furnaces for billets or inline heating of the intermediate bar.

A special philosophy in wire rod mills is to use a flexible roll pass design, or flexible grooves with high working range. By means of flexible roll pass sequences, the intermediate rolling can be carried out in the same grooves for a wide range of finished products, simply by changing the roll distance. Thus groove changing can be replaced by a simple shifting of the roll gap, which reduces the downtime for changing from one product to another. The target of the research, presented in this thesis is mainly to establish a flexible method of rolling in order to improve the mill utility and efficiency without jeopardising the quality.

An example of utility for a common wire rod mill is shown in **Figure 5**. The utility of a mill ranges from typically 40 % for one of very complicated production consisting of a wide range of sizes and steel grades, up to 85-90 % for a high performance wire rod mill, rolling only a few dimensions and steel grades [15, 16].
Figure 5. A typical structure for utility in wire rod production from rolling billets to wire rod products accepted for delivery.

The downtime is grouped into four or five main groups.
- Mechanical and electrical problems in the equipments.
- Changing rolls, grooves and other parts in the line.
- Shortages i.e. waiting for correct heating temperature when changing steel types, shortage of billets or lack of operators.
- Cobbles and quality problems.

By means of a flexible roll pass design, the changing and adjustment time, shown in Figure 5, will be reduced since most of the groove changes are replaced by simple adjustments of the distance between the rolls. Further, cobbles and mechanical downtimes will be decreased due to safer resetting of guides and rolls. Thus, also the yield will be improved.
5. Quality

Today the annual production of stainless steel wire rod is about 1,3 Mt in the world [17]. The main end applications are wire for welding, cold heading, springs, and for general purpose. Also wire rods for surgery and special applications within the chemical and petroleum industry are demanded. For many applications, such as cold heading and spring wire, the current quality demand is “zero defects”.

The yield is measured in all production steps. Typical yield distributions from billets to finished wire rod products are presented in Figure 6. In wire rod mills the head and tail ends are cut in shears in the rolling process in order to take away cold, broken or spit up ends. Average losses are 2-3 % for end cutting. In the furnaces and during rolling, material is lost as oxide scale. For stainless steel the scale is quite thin compared to carbon steel and the losses mainly appear as thin dust and smoke. The scale losses are estimated to an average of 1,2 %. Most stainless steel wire rod is pickled in sulphuric acid (H₂SO₄) or mixed acids of hydrofluoric acid (HF) and nitric acid (HNO₃). The pickling losses are estimated to an average of 0,8 %. More disastrous are losses due to cobbles and rejections of non-conforming products, since cobbles are followed by downtime for cobbles cleaning and in worst-case reparation of different mill parts. Rejections because of non-conforming products disturb the market relations and give bad reputation.

![Yield in Wire Rod Production](image)

**Figure 6.** A typical structure for yield in wire rod production yield from heating the billets to finished wire rod products accepted for delivery.

To compare wire rod mills is quite difficult. The amounts of losses are different depending on the mill layout, the rolled steel grades and the mix of product
sizes. In a modern mill, with a not too complicated product program, the yield shall exceed about 96 % [15, 16].

Inner quality and structure are important e.g. grain size, slag inclusions and in stainless steel also carbides. In wire rod rolling in high-speed blocks, the accumulated deformation increases the temperature locally in the wire rod and can cause melting of segregated areas in some high-alloyed steels.

Scratches, inclusions and surface cracks are not acceptable for spring wire, cold headings and wire lines. The thesis includes an analysis of the behaviour of longitudinal V-shaped surface cracks located at three different positions along the wire circumference. This is done for three different reductions. The necessity of a high billet quality in relation to the roll pass design and the requirements of wire rod quality is also investigated.
6. Flexibility and Working Range in Wire Rod Rolling

In wire rod rolling of mixed steel grades and dimensions, grooves and guides are limiting the mill flexibility. Different pass designs have different characteristics. The Swedish co-operative steel research, organised by Jernkontoret (The Swedish Steel Producers’ Association), has performed a series of research projects treating reduction capability, flexibility and working range for different roll pass sequences [18–22]. Wallner [20] defined the working range of the oval–square sequence, by defining the ratio of thickness of oval edge \((OE)\) over the diameter \((DS)\) of the corner fillet in the succeeding square groove. Definitions of the parameters are shown in Figure 7. The range was set with the lower limit 0,25 not to obtain heavy wear in the groove bottom and the upper limit 0,71 not to extrude material up in to the groove bottom and create multiple folds, wrinkles or scratches in the corner, often called “cat scratches”.

6.1 Roll Pass Design

The function of the grooves is to reduce the cross-sectional area and elongate the bar efficiently, i.e. with a low amount of spread. Common grooves are rectangular box grooves, diagonal grooves such as squares and rhombic grooves (diamonds), and round or false round grooves as well as oval grooves. In production, a combination of grooves is named, “pass design” or “groove series”. An entry bar rolled in a groove to an exit bar is defined as a “sequence”. A ”series”, means a schedule of sequences built up by two or more “grooves”. Figure 7 shows four examples of common roll pass sequences and Table 1 different combinations of rolling sequences.
Figure 7. Geometrical definition used for bars and grooves. • Supplement A.

Table 1.
Combinations of rolling sequences for an entry bar rolled in a groove to an exit shape.

<table>
<thead>
<tr>
<th>Entry bar → Exit bar</th>
<th>Flat / Box</th>
<th>Oval</th>
<th>Edge oval</th>
<th>Diamond</th>
<th>Square</th>
<th>False round</th>
<th>Round</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat / Box</td>
<td>Used</td>
<td>Possible Used</td>
<td>Used</td>
<td>Used</td>
<td>Possible</td>
<td>Possible</td>
<td>Round</td>
</tr>
<tr>
<td>Oval</td>
<td>Used</td>
<td>Used</td>
<td>Used</td>
<td>Common</td>
<td>Common</td>
<td>Possible</td>
<td>Common</td>
</tr>
<tr>
<td>Edge oval</td>
<td>Used</td>
<td>Used</td>
<td>Common</td>
<td>Common</td>
<td>Possible</td>
<td>Possible</td>
<td>Common</td>
</tr>
<tr>
<td>Diamond</td>
<td>Used</td>
<td>Used</td>
<td>Common</td>
<td>Common</td>
<td>Possible</td>
<td>Possible</td>
<td>Common</td>
</tr>
<tr>
<td>Square</td>
<td>Possible</td>
<td>Common</td>
<td>Common</td>
<td>Common</td>
<td>Possible</td>
<td>Possible</td>
<td>Used</td>
</tr>
<tr>
<td>False round</td>
<td>Used</td>
<td>Common</td>
<td>Possible</td>
<td>Common</td>
<td>Used</td>
<td>Possible</td>
<td>Used</td>
</tr>
<tr>
<td>Round</td>
<td>Used</td>
<td>Common</td>
<td>Possible</td>
<td>Common</td>
<td>Used</td>
<td>Possible</td>
<td>Used</td>
</tr>
</tbody>
</table>

Common roll pass design in bar and wire rod mills include box grooves, diamond–diamond and diamond–square for heavy sections and square–oval, false round–oval or round–oval for medium sections and wire rod. During rolling the bars are turned 90° after exiting a groove and before entering the succeeding one, except for a square, which is twisted an angle of 45° before entering the oval. When using round–oval or false round–oval it is common to install the roll stands in alternately horizontal and vertical position to get rid of the necessity to twist the bar during rolling. Roller guides are used to stabilise the oval bar in the false round or square grooves. False round and square bars are only in the need of simple guides to have them enter the oval grooves.
Working range or flexibility for grooves normally means the possibility for a single groove to deliver a bar with well-defined shape from a given entry section [20]. For a series of grooves, the working ranges for the single grooves are connected to those of the previous and the following ones [22]. All sequences of grooves are connected and inter-linked with each other in the pass design. A calculated working range for rolling bars of $\phi$ 28 mm, in six oval–false round passes is presented in Figure 8.

![Figure 8](image)

**Figure 8.** Working range, illustrated by the vertical distance between the two curves, for an entry bar of $\phi$ 28 mm rolled in six passes of oval–false round etc..

A good pass design must guarantee stable rolling and shall enable a long running time [23]. The bar must be easy to guide, to reduce the risk for surface scratches, cobbles. It is an advantage to use the same intermediate grooves for many final dimensions.

### 6.2. Properties of Different Pass Sequences

The reduction capacity of different roll pass series is presented in a work of Collin [18]. Common average reductions, for some sequences used in industry are shown in Table 2.
<table>
<thead>
<tr>
<th>Serie</th>
<th>Mean reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square–oval</td>
<td>25</td>
</tr>
<tr>
<td>False round–oval</td>
<td>17</td>
</tr>
<tr>
<td>Round–oval</td>
<td>20</td>
</tr>
<tr>
<td>Diamond–square</td>
<td>24</td>
</tr>
</tbody>
</table>

Limits for the square–oval series are the fitting of the oval edges into the square groove bottom. The ratio of width over height of the oval should be in the range of 1,5-3,5. A quite severe limit is that the ratio of diagonal length of the square should be in the range of 0,95-1,05. Otherwise the rolling in the following oval will be unstable.

Typical characteristics for a modern flexible roll pass design used in the Fagersta Stainless AB wire rod mill are shown in Figure 9 and Table 3. 150 mm square billets are reduced in thirty passes down to round ø 5,60 mm. The pass design is unchanged from roughing and intermediate rolling down to 24 mm square. After that the roll gaps are adjusted depending on the required final dimension and on different steel grades having different flow stress and spread behaviour.
Figure 9. A modern flexible pass design found in the Fagersta Stainless AB wire rod mill. Square cross-sections of 24 mm are rolled to final rounds 5.60 mm. Supplement B.
Table 3.
Groove measures in the Fagersta Stainless AB wire rod mill.

<table>
<thead>
<tr>
<th>Groove</th>
<th>Shape</th>
<th>Width [mm]</th>
<th>Height [mm]</th>
<th>Side [mm]</th>
<th>Bottom Diameter [mm]</th>
<th>Roll gap [mm]</th>
<th>Opening angle [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>oval</td>
<td>34.2</td>
<td>16.1</td>
<td></td>
<td>51</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>square</td>
<td>23.5</td>
<td>21.7</td>
<td>18.2</td>
<td>10</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>oval</td>
<td>27.8</td>
<td>12.8</td>
<td></td>
<td>41</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>square</td>
<td>18.7</td>
<td>17.2</td>
<td>14.2</td>
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6.3 Influence of Interstand Tensions

Interstand tensions are usually avoided as much as possible in wire rod rolling because otherwise the head and tail ends will be out of tolerances since the free ends cannot be rolled with tensions. This fact should result in overfilled grooves and end-defects such as fins. However in high-speed wire rod blocks with six to ten stands with fixed transmission, interstand tensions are used to obtain stable rolling conditions. In that case the grooves are set to give the required tolerance when the interstand tensions are applied to the rolled bar. In order not to be forced to cut the heavy head and tail ends, automatic gap control systems can be used in the two last stands upstream the wire rod blocks.

The European standard (EN 108 or DIN 59115) for wire rod dimensions and tolerances for round 5.69-10.00 mm is ±0.15 mm, with a maximum ovality, or the difference between maximum and minimum dimensions over a cross-sections, of 0.18 mm. In the speciality steel plant at ABS in Italy, tolerances ±0.065-0.125, depending on product size, are reported [24]. By using a twin module block (TMB) tolerances of ±0.10 mm can be obtained [15]
7. Summary of Appended Papers

The five papers included in the thesis are focused on flexibility, productivity and product quality in the rolling of steel bars and wire rods.

Flexibility or more precisely the working range for series of two-symmetrical grooves in wire rod rolling makes up the main issue of the work. A large working range for a flexible rolling series means that different product dimensions for different steel grades can be manufactured with a minimum of groove changes. The spectrums of wire rod cross-sections are obtained by simply changing roll gaps in an adequate way. The working range is of course also limited by the necessity that the product must fulfil the customer demands considering a high quality wire, free from outer and inner defects.

The relation between the papers is clear from Figure 10.

![Diagram showing the relation between the papers](image)

**Figure 10.** Relation between the appended papers.

The limits of the working range are defined, modelled and analysed for a false round–oval series in *Paper A*.

*Paper B* deals with the verification of a working range model by means of laboratory trials and measurement under industrial conditions and its application for process development within Fagersta Stainless AB.
In Paper C the behaviour of surface cracks is studied as a function of the pass reduction for a flexible false round–oval roll pass design. FE-calculations are carried out and functions for decreasing surface defects during rolling are formulated.

Paper D considers the influence of interstand tensions on the flexibility. The working range for grooves are modelled and analysed.

Finally Paper E treats the possibility to make use of interstand tensions in intermediate blocks for enabling an increased rolling speed, without getting problems when rolling high alloy steels due to local temperature increase and formation of internal defects.

7.1 Paper A. “Working Range for Sequences and Series of Two Symmetrical Grooves in Wire Rod Rolling”

The conception “working range” also called “flexibility” for sequences and series of grooves is defined. A computer program “WORKRAN” is developed to calculate the working range for series of two-symmetric grooves including “oval”, “round”, “false round”, ”square” and “diamond” shapes.

The program uses the Wusatowski spread model [24], and the bar cross-section is transformed to an equivalent rectangle by Lendl’s method [25]. Limits for exiting bar shapes, fitting factors, minimum reductions, maximum angles of bite etc. are defined. The program calculates the maximum roll gap to fulfil the limitation for the exit bar in the first groove. When the roll gap is found, the exit bar is used as entry bar to the second groove. The program adjusts the roll gap, until the filling of the next groove is within defined limits and all additional criteria area fulfilled.

Results from WORKRAN are presented in Figure 11. The upper and lower limits for different kinds of sequences are marked as dotted or full lines.
**Figure 11.** Working range, as determined from the computer program WORKRAN for three passes of round–oval–false round–oval in three different pass designs. Theoretical calculation.

The working range is smaller for pass sequences designed for high reductions.

The model is evaluated in laboratory tests in “round”—“oval”—“false round”—“oval” sequences. In addition, full-scale experiments considering the “square”—“oval” were carried out at Fagersta Stainless AB. Necessary improvements in the roll pass design are suggested.

### 7.2 Paper B. “Flexibility and Utilization of Roll Pass Sequences in Some Swedish Wire Rod Mills”

This paper deals with the verification of the “WORKRAN” model by means of results from laboratory trials at the Swedish Metallurgical Research Institute (MEFOS) and the Royal Institute of Technology (KTH) and measurements from full-scale sequences at the plant in Österbybruk and Fagersta. **Figure 12** shows an example of a working range calculated with “WORKRAN” and six different mean reductions evaluated from the laboratory trails.
Figure 12. Theoretical calculated working range for the KTH series of six experimental reduction series. A comparison between theory and experiments.

Comparisons are also made with roll pass series reported by Mauk [26]. It is shown that “WORKRAN” is developed for relevant rolling conditions, Figure 13, and represents a useful tool for roll pass design analysis.

Figure 13. Reduction series for the compared pass designs. Experimental results with the exception of theoretical results obtained by Mauk.
A roll pass design used at the plant in Hofors is analysed. By changing from square–oval to false round–oval in the last four passes before the finisher, the entire rolling program from φ 5.5 to 20 mm could be rolled without groove changing in the intermediate mill.

A new series in Fagersta Stainless AB, including false round–oval sequences is analysed. The eight last stands are mounted in the wire rod block, where the reductions are fixed. The pass design in the block is always oval–round, see Figure 9. Figure 14 shows the reduction series from 24 mm square to final round dimensions in wire rod block. From 24 mm square the roll gaps and grooves are changed for rolling different final dimensions.

![Logarithmic areas in late part of inter-mediate train and in wire rod block](image)

**Figure 14.** The reduction series used in the wire rod mill at Fagersta Stainless AB. Square bars of 24 mm to different final round dimensions in a wire rod block. Experimental results

The improved pass series in Fagersta made it possible to roll the wide stainless steel product program with only three roll pass families in the wire rod block.

### 7.3 Paper C. “Surface Cracks in Wire Rod Rolling”

The behaviour of artificial cracks, milled in the longitudinal direction of the billet surface, has been investigated for rolling in a six passes false round–oval series.
Cracks were made along 28 mm round high-speed steel bars SS2722 (AISI/SAE M2). The cracks were V-shaped with an opening of 0.5 mm and a depth of 1.7 mm. The positions of the cracks when rolled in the different passes are shown in Figure 15.

![Diagram of rolling passes with labels 1, 2, and 3]

**Figure 15.** Positions of V-shaped artificial cracks denoted 1, 2, and 3 in the experiments.

The depth of the crack after rolling is related to the original crack depth on the entry bar surface and thus an “equivalent crack depth” is defined. This parameter is then correlated to the shape and cross-sectional area of the bar to make it possible to evaluate whether the defect has become more or less harmful after rolling. Thus a “relative crack depth” is defined. This parameter equals 1 when the crack depth decreases in direct proportion to the billet cross-sectional area. Smaller values indicate that the crack depth decreases more rapidly than the cross-sectional area, resulting in a comparatively shallow crack. **Figure 16** shows an example how the three cracks 1, 2, and 3, behave in a series with 23 % average pass reduction. When the cracks are up to favourable deformation conditions, the slopes of the curves are heavily negative.
Figure 16. Relative depth of the V-shape cracks \{1\}, \{2\} and \{3\} – initial depth 1.7 mm and initial opening 0.5 mm on round entry bars round 28 mm.

In the false round–oval sequences, a surface crack in the groove bottom, \{1\}, may open up during rolling at the same time as its depth is reduced more rapidly than the cross-sectional area of the billet. This is a beneficial situation. However detrimental conditions are found for cracks at 45°, \{2\}, and on the free sides of the wire rod, \{3\}. The latter cracks are reduced in depth but they are not opened up. Instead they are closed. The closing of the cracks, means that the two oxidised surfaces of the crack get into contact and hidden rolled-in oxides, constituting a defects beneath the surface, are created.

During the subsequent oval–false round sequence, the crack in the groove bottom \{3\} decreases its relative depth, while the relative crack depths on the free side \{1\} and at 45° direction increase. All cracks are now closed.

From a previous investigation [20] it is concluded that flat oval grooves are better than round ovals, and false rounds are superior to squares for opening and decreasing the depth of longitudinal cracks.

A FE-analysis of the two first passes is carried out to explain the experimental results. Figure 17 shows the effective strain for a round bar reduced in an oval groove. The “warmer” the colours the larger the effective strain. The local radial strain component can be a measure of the reduction of the crack depth in
a pass. A positive tangential strain component is favourable for not closing the crack.

Figure 17. Effective strain distribution obtained from a FE-analysis for a round-oval sequence.

Figure 18 shows the local strain components at the free bar side surface as a result from a round-oval sequence. Compression is obtained both in radial and angular direction (tangential) and elongation in longitudinal direction. This indicates that the crack depth becomes smaller and that the crack gets partially or totally closed resulting in a Y- or I-shaped crack.
Figure 18. Strain components in the longitudinal, angular and radial direction obtained on the bar surfaces for a round-oval sequence on the free side corresponding to the position of crack (3).

7.4 Paper D. “Working Range of Roll Pass Sequences in Wire Rod Rolling with Interstand Tensions”

In high speed rolling in wire rod blocks, interstand tensions are utilised in order to keep the process stable. The level of such tensions influences the rolling process, especially the spread and forward slip. Usually the tensions are kept as low as possible in order to obtain the required tolerances. However, such tensions can be used for increasing the working range of a pass sequence and move the product range towards smaller sizes. A practical problem with this method is the fixed gearings in the common blocks, which require a certain and given level of the interstand tensions and corresponding reductions. The influence of tensions is analysed for a typical six-stand wire rod block with one motor and fixed transmission. A model showing the basis for the calculations procedure in relation to the block is shown in Figure 19.
Figure 19. Model showing the basic calculation procedure for analysing the influence of interstand tension on the working range in a wire rod block.

For this purpose a computer program “TENSION” [27], developed at the Royal Institute of Technology in Stockholm, dealing with the basic principles of rolling with interstand tensions is combined with “WORKRAN”. Figure 20 shows how the minimum exit area of each pass is reduced compared to rolling without interstand tensions in a six-stand block. At a tension level of 10% of the material yield stress, the minimum exit bar cross-sectional area is reduced by 7
The influence of interstand tensions on this level on the working range is negligible.

![Diagram](image)

**Figure 20.** The influence of interstand tensions on reduction of cross-section area in each pass compared with tension free rolling. Oval-false round series.

High-tension levels have a large effect both on the extension of the working range and on the reduction of the minimum exit area. However, it becomes more difficult to control the rolling stability and the product tolerances at higher interstand tension levels. The influence of interstand tensions on the area reduction and on the working range of the pass sequence is heavily pronounced for the round passes, shown by the steep negative inclinations of the curves, while the oval grooves have an opposite effect especially at high tension levels.

7.5 *Paper E.* “Ultra-high Speed Rolling of Stainless Steel Wire Rod by means of Interstand Tensions”

When high alloy stainless wire rod is rolled at high speeds, defects often occur. The reason for this is that the flow stresses of such materials are higher than for ordinary low alloy steels. Furthermore the deformation over the cross-sections is far from homogenous. The result is extremely high material temperature caused by adiabatic heating. In the extreme cases impurities within the steel such as certain types of slag inclusions might even melt and liquid phase penetrates the
grain boundaries of the microstructure, resulting in cobble. Even if the rolled
wire product is free from obvious defects, the microstructure might not fulfil the
demand of the customer such as a homogenous microstructure all over the wire
cross-section. Figure 21 shows an example where the grain size varies over the
cross-section. Thus the finish rolling speed in stainless steel rolling is limited to
approximately 60 m/s, while simple carbon steels and low alloy steels can be
rolled at speeds above 100 m/s.

Figure 21. Example of variable distribution of grain size over an oval cross-section from
wire rod rolling.

By means of modern control technology, roll stands can be separately driven
and controlled at very high speeds. Thus the eight stand blocks can be
subdivided into two four plus four passes blocks with a cooling section in-
between. In a revamp situation the short distances can be limiting the possible
cooling and equalization lengths, and it may be necessary to reduce the number
of passes by increasing the reductions upstream in the mill, where the speed is
low. One possibility to do that is to introduce interstand tensions on a reasonable
level upstream the finishing block.

A case study shows that the finish rolling speed can be raised from 60 to 80 m/s,
by reducing the number of passes. Here two passes could be taken away by
introducing interstand tensions not exceeding 10 % of the material yield stress in
the intermediate rolling at the same time as cooling lines before a new four stand
finishing block were installed. Heavy ends caused by the lack of interstand
tensions when rolling the head and tail ends must however be compensated by
means of automatic gap control.

Thanks to this configuration the roll pass sequences could be simplified by
utilizing the single family rolling principle meaning that all resetting and size
changes are preformed in the finishing block, while the setting of the upstream
mill is remained unchanged simply by taking suitable feeder sizes from the
intermediate mill to the finishing block. Together with fast changing equipment and the ready to roll concept, meaning that all rolling equipment is pre-set in the workshop, considerable reductions of the mill downtime could be obtained and trial bars will no longer be necessary.
8. Discussion

Wire rod mills usually have lower OEE than other kinds of mills because of the higher downtime for roll- and stand changing and groove and guide adjustments when shifting products. Even if much efforts have been made by the mill manufacturers to reduce the downtimes, for instance by fast stand and groove changing equipment for simultaneous changing of groups of stands, still much is left to do, for example improvement of roll pass design and rolling technology in order to increase the value enhancing running time.

The program “WORKRAN”, developed within the project, has proven to be an efficient tool in calculating the working range for a given roll pass design, and together with a computerised roll gap setting system, the entire intermediate mill can be reset in the gap time between two billets. In such a case the finishing rolling must be organised in a way that different stands or groups of stands can be used as finisher, in order not to lose time in resetting the finisher.

Even if an important part of the losses in the mill can be reduced by means of a flexible roll pass design, still nothing has been possible to do considering the speed losses and gap time losses. The gap time losses are purely a function of billet weight and the actual gap time, and cannot be influenced by the roll pass design.

In a wire rod mill, rolling plain carbon steel, the speed losses are mainly a problem when rolling the smallest sizes. For instance the maximum mill speed is used for the three or four smallest sizes, which means that the productivity when rolling \( \phi \) 5,6 mm wire rod is only 64 % of maximum mill capacity, reached when rolling \( \phi \) 7,0 mm wire rod at the same speed. When rolling high alloy steels such as tool steels and stainless steels, the possibility to improve the productivity by increasing the rolling speed is limited. One reason for this is the basic fact that these materials often are very hard and need a lot of plastic work for the deformation, resulting in very high temperature rises. In a modern wire rod block where six to ten stands are mounted in common frame with an interstand distance of the order of one meter, a lot of plastic work is accumulated in the rolled material and the temperature raise is considerable. Therefore high alloy steels have a tendency for local melting in segregated areas when the rolling speed is increased. This effect strengthened by the uneven strain distribution over the cross-section. One way could be to develop new rolling series with the focus on minimizing heavy local strains. A promising concept treated in the thesis is discussed below.

This problem of local high temperatures cannot simply be solved by means of a flexible roll pass design. However, by introducing interstand tensions in the
intermediate stage of rolling, where the rolling speed is lower and the interstand distance usually is three to six times that in the wire rod block, it is possible to reach the block with a smaller cross-section, that needs only four to six passes instead of eight to ten. This is possible since the pass reduction is increased due to reduced spread when rolling with interstand tensions. The smaller cross-section is easier to cool, and due to the lower the accumulated strain in the wire rod block, the temperature can be kept on a safe level, even at a higher finish rolling speed. However, it is important to make sure that introduction of interstand tensions does not reduce the flexibility of the intermediate roll pass series.

It is shown that the flexibility or working range for a typical false round–oval sequence is slightly increased when interstand tensions of the order of 10 % of the actual yield stress is applied during rolling, but the increase is negligible. By means of higher tension levels larger improvement of the flexibility can be gained, but it can also be disastrous for the surface quality and cause cobbles in the mill. In this context the meaning of yield stress refers to an estimated average value over the cross-section based on data from literature. The determination of more adequate values of the average material yield stresses than those used in the present work should be valuable, especially for the higher speed range. However, flow stress data for extremely high strain rates are not available today. The average yield stresses could have been estimated by means of well-trusted formulas if the rolling forces for the different stands had been measured. However, also this method should only result in rough estimations since for example the conditions of frictional in the roll gaps are not well known.

In a research program like this, it is important to make sure that the roll pass series has the ability to produce wire rod free from defects in the entire working range. From the experiments carried out, experiences have been gained to evaluate the decrease of surface defects when rolling in the entire working range of the false round–oval series. It must be pointed out that this work is just started and a lot more must be done, especially by means of finite element simulations, in order to be able to predict the surface quality of wire rods, rolled in a given pass design. When that job is finished an additional way of reducing production costs will become possible since a certain billet quality can be determined as a function of the roll pass design.
9. **Conclusions**

- The program “WORKRAN”, developed within the project, has proven to be an efficient tool to calculate the working range for a given roll pass design.
- By combining “WORKRAN” and “TENSION”, the program can be used even for analysing rolling with interstand tensions.
- Together with a computerised roll gap setting system, “WORKRAN” can be used as a tool for roll gap resetting.
- When a flexible roll pass design is used in the intermediate mill, resetting of the finishing mill will limit the possible gain in downtime.
- A flexible roll pass design is an advantage for product development when new sizes or steel grades are introduced.
- By means of a flexible roll pass design the risk for groove overfilling and the creation of cobbles when changing steel grades can be minimised.
- There is a strong interdependence between the flexibility of the roll pass design, the utility of the mill and the yield.
- By means of a flexible roll pass design important improvements of the value enhancing running time can be gained, at least in mills used for large spectrum of steel grades and final dimension.
- When rolling high alloy steels, the possibility to use high speeds is severely limited since all plastic work is transformed into heat in the rolled material and the temperature raise is considerable, meaning a high risk for defect formation.
- By introducing interstand tensions in the intermediate stage of rolling, it is possible to reach the block with a smaller cross-section that needs only four to six passes. Resulting in lower temperature raise in the finishing block.
- The flexibility for a typical false round–oval sequence is slightly increased when interstand tensions of the order of 10 % of the actual material yield stress is applied during rolling.
- Surface defects in a billet can be reduced when rolling in a false round–oval series. Favourable conditions are characterised by crack opening at the same time as the crack depth decreases more rapidly than the cross-section of the billet. Closed cracks mean risk for serious oxide defects hidden under the wire surface.
References


[10] Orbis® – The next generation compact cost-competitive version of globally established Orbis gauge system, Brochure from IPL Integrated Photomatrix Inc, Dorchester, Dorset DT3SY, UK.


