Evolution of artificial defects during shape rolling

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Abstract

Very often defects are present in rolled products. For wire rods, defects are very deleterious since the wire rods are generally used directly in various applications. For this reason, the market nowadays requires wire rods to be completely defect-free. Any wire with defects must be rejected as scrap which is very costly for the production mill. Thus, it is very important to study the formation and evolution of defects during wire rod rolling in order to better understand and minimize the problem, at the same time improving quality of the wire rods and reducing production costs.

The present work is focused on the evolution of artificial defects during rolling. Longitudinal surface defects are studied during shape rolling of an AISI M2 high speed steel and a longitudinal central inner defect is studied in an AISI 304L austenitic stainless steel during ultra-high-speed wire rod rolling. Experimental studies are carried out by rolling short rods prepared with artificial defects. The evolution of the defects is characterised and compared to numerical analyses. The comparison shows that surface defects generally reduce quicker in the experiments than predicted by the simulations whereas a good agreement is generally obtained for the central defect.

Keywords: shape rolling, wire rod rolling, artificial defects, defect evolution, surface cracks, porosity, FEM, high speed steel, stainless steel
Preface

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My companion in life, Nedjo for filling my life with extraordinary joy.

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1. Introduction

Hot rolling, using grooved rolls, is an important industrial method of producing bars and wire rods of round cross sections. The deformation process does not only reduce the cross section and lengthens the rolled bar, it also improves the properties, such as strength and toughness, of the primary cast metal by refining the grain size and improving homogeneity. The strain distribution during rolling is characterised by the area-reduction ratio, the strain rate and temperature history, as well as the chemical composition of the rolled steel. All of these variables together with the roll pass design have a strong influence on the shape and quality of the final product.

In many commercial wire rod rolling mills, the prime concern is to produce an appropriate cross-sectional shape and area rolling as quickly as possible and using as few passes as possible in order to increase market satisfaction and productivity. Dimensional accuracy and quality of the wire rod are very important, since these wire rods are normally used directly in many applications. It is thus impossible to accept products with any marks, scratches, shells, cracks, overfills or oxide particles on the surface.

Nowadays in the steel industry, demands on quality, dimensional tolerances and mechanical properties of the rolled products are increasingly becoming more rigorous. In addition, many high-alloyed steels have a narrow temperature interval for rolling. At low temperatures, the flow stress becomes too high and the process is limited by the maximum rolling force of the mill. At high temperatures, on the other hand, there is a risk of partial melting in grain boundaries because of the intense deformation heating during rolling. In such cases the bar collapses during rolling. Thus, in order to control the rolling process, many rolling mills of today have on-line gauge measurement systems and on-line gap adjusting procedures [1]. The improved process controls of the rolling mills guarantee that the required product properties are met with a minimum of scrap production.

In hot rolling of wire rods, the deformation behaviour of the rolled billets is very complex and because of this, roll pass design is, at present, essentially a trial-and-error procedure. The pass design sequences usually used in mills are “square-oval” and “false round (round)-oval”, but it is also common to use “diamond-square” and “diamond-diamond” sequences. As the market demands for high quality wire rod increases, it is of great importance to better understand how defects behave during rolling and how the roll pass design affects the evolution of defects. As a result, this thesis includes an experimental and a numerical analysis of the behaviour of surface and inner defects during high speed rolling.
1.1. Roll pass design
Roll pass design is an important field of rolling mill technology. In bar and wire rod rolling using grooved rolls, the cross-sectional area is reduced and the bar is elongated with large lateral spread. The function of roll pass design is to ensure the production of the desired shape, good surface without any defects and at the lowest possible cost [2]. A good series of grooves must guarantee stable rolling. The most common pass design sequences used in intermediate mill are “square-oval” and “false round (round)-oval”. It is also common to use “diamond-square” and “diamond-diamond” sequences upstream in the rolling mill. In the roughing mill, also box grooves are common. The characteristics of the square-oval and false round-oval sequences are shown in Fig. 1.

False round-oval series are very popular in continuous mills. The reason is that the series are gentle to the bar and have high flexibility. The reduction capacity is lower than for square-oval series and is usually about 17% per pass, but can be considerably higher when using flat ovals [3]. Twisting of the bars is eliminated in this series by arranging the stands in alternating horizontal and vertical position. It could be mentioned that roller guides are needed for guiding the oval bar into the false round grooves, see Fig. 1a, b.

![Fig. 1 Common sequences in wire rod rolling: a) oval-false round, b) false round-oval, c) square-oval and d) oval-square [4].](image)

The square-oval series are stable and have a relatively high reduction capacity. Average reduction is about 25% per pass. The “square” is twisted 45° before entering the oval groove. After reduction, the “ovals” are turned 90° before entering the square groove. This series is not recommended for rolling of heavy
sections. When a “square” is twisted 45° before entering the oval groove, they can become distorted. In addition, the corner of the “square” is too sharp to fit in the oval groove, and because of that, the oval grooves are worn out very fast causing high cost and extra downtime for roll replacement. Normally, roller guides are used to stabilise the oval bars before entering the square grooves, see Fig. 1c, d.

A special sequence is round-oval, which compared to false round-oval gives lower flexibility. This pass design is commonly used in finishing rolling sections such as wire rod blocks.

Diamond-square, or diamond-diamond, sequences have lower reduction capacity than the square-oval series, about 20%. The series are stable and commonly used in roughing mills where the bite angle is large [5]. Diamond-square series are seldom used in rolling because of the high rolling force and risk for bite problems. Even problems with uneven bar temperature distribution can arise. The corners of the bar are cooling down much faster than the bar sides and centre causing a risk for corner cracks due to high tensile stresses.

1.2. Aim of the work
This work analyses the wire rod rolling process in order to better understand the behaviour of defects during rolling. Two types of defects are considered. Longitudinal surface defects and a central longitudinal cavity, the former representing longitudinal surface cracks and the latter a string of pores. The employed methods include both experimental and numerical work in order to allow a comparison between the two methods. In recent years, numerical simulations tend to replace costly and time consuming experiments. In addition, the numerical analyses present a method of studying the deformation behaviour in detail, which is very tricky experimentally. Thus, there is a strong need to validate the predicted results from calculations with experimental investigations. When a numerical method is reproducing the experimental data satisfactorily it is, in principle, possible to examine the effect of various process parameters on the quality of the rolled product. In this respect the final step in wire rod rolling is the main focus since the largest deformation rates appear there resulting in the most severe deformation conditions.

The aim of this thesis is to investigate the evolution of defects using 3D FE simulations of wire rod rolling in a wire rod block using a FE program MSC.Marc. The most important details and results will be presented in the thesis whereas more precise and detailed information is presented in the appended papers.
2. Rolling

Normally cast billets of near quadratic cross section are used as raw material when a wire is being produced. At Fagersta Stainless AB, being studied in the present thesis, quadratic billets of 150 mm$^2$ cross section, 6200 mm length and 1050 kg of weight are used. Suppliers of stainless steels are generally Outokumpu SMACC, Sheffield, UK, or AB Sandvik Materials Technology, Sweden. A layout of the rolling mill is given in Fig. 2. Next, the details will be discussed.

![Diagram of the rolling mill at Fagersta Stainless AB](image)

**Fig. 2** Layout of the wire rod mill at Fagersta Stainless AB.

2.1. Heating

The wire making process starts by placing the billets in a so-called “walking beam furnace”. The name reflects that the billets are lying on parallel beams in the furnace moving up, forward, down and back in order to move the billets through the furnace. The furnace itself has three zones with variable temperatures depending on the material being rolled. The final temperature may vary from 1050 and 1300°C in this respect. The cycle time for the billets in the walking beam furnace is about 3 h but can be much longer under down-time in the rolling mill. Normally, the processing in the rolling mill is very quick. Typically a billet is rolled down to a wire of diameter 5.6 to 13.5 mm in only 10 minutes.

2.2. Roughing mill, reversing mill and intermediate train

First, the billet enters a reversing roughing mill (schematically illustrated in Fig. 3) where it is rolled in two box grooves down to 125 mm$^2$ cross section in three
passes. Then, it enters a reversing duo mill with seven passes (diamond-diamond-diamond-square-boxoval-boxoval-round) where it is rolled down to a round cross section of diameter \( \approx 60\) mm. During rolling in the duo mill, the temperature of the billet has dropped from about 1050°C to about 950°C at the head end and to about 880°C at the tail end. The temperature of the bar is then raised to 1000°C by passing a high frequency furnace before entering an intermediate train (illustrated in Fig. 4) with 12 passes (oval-round-oval-round-oval-square-oval-square-oval-square-oval-round) at a speed of approximately 0.65 m/s. As the bar exits the intermediate train it has a round cross section with diameter 12.7-14.5 mm and an exiting speed of about 12.5-14.5 m/s. Then, the bar passes a short quenching zone lowering the temperature to about 940-960°C before entering a wire rod block.

Fig. 3 An illustration of an old roughing mill [6].
2.3. **Wire rod block**

The wire rod block consists of eight pairs of rolls driven by one motor through a fixed gearbox producing an oval-round-oval-round-oval-round-oval-round profile, see Fig. 5. The stands in the wire block are tilted ±45° from the vertical line and are evenly distributed along the rolling line. Three main series “5.6 mm”, “6.0 mm” and “6.5 mm” are used to produce finished dimensions of the same diameter. The average reduction is 17.2% in the round sequences and 18.6% to 19.7% in the oval sequences. The finished rolling speed for the three series is 60, 52 or 40 m/s depending on the steel grades. Due to the high rolling speed it takes only about 90 s for a whole heat to pass a stand in the mill.
2.4. Final treatment

The wire rod produced in the wire-rod block runs out in a “quenching” zone where it is laid in a spiral (Fig. 6) and quickly quenched in cold water. The spirals are then collected and packed as coils. The coils may be delivered in the “hot rolled“ condition or after being soft annealed in bell furnaces at a peak temperature of 1070°C for 15 min with a total cycle time of about 3 h.

Fig. 5  The wire-rod block at Fagersta Stainless AB, with open hood. The rolling direction is from left to right in the figure.

Fig. 6  Laying of finished wire in a spiral.
3. Defects

3.1. Classification
Different defects can occur in rolled bars and wire rods. Verlag Stahleisen in Germany has published an atlas of different wire-rod defects [7] dividing them into three groups according to:

- defects developed from metallurgical practice or from the chemical composition of the rolled steel
- defects developed from improper mill practice
- defects developed from improper roll pass design

3.2. Metallurgical defects
Localized impurities in billets, shrinkage cavities and segregation may give cracks in the billets. Incorrect dimensions, bent, twisted or rhombic billets can cause serious defects such as cobbles, i.e. disintegration of the bar, during rolling. Thus, in order to improve the surface quality of the final products it is often necessary to grind the billets before rolling.

Longitudinal surface cracks are often found on continuously cast slabs and are located in regions close to the centre line of the slab surface. They are very difficult to eliminate during subsequent hot rolling and will remain as defects in the rolled product [8].

3.3. Defects from improper mill practice

3.3.1. Cracks and scratches
By experience, the most common defects in wire rods are cracks and scratches. Cracks, see Fig. 7, can be caused by improper roll pass design, damaged roll surfaces, worn out grooves and coarse scale rolled into the surface of the rolled product. Cracks can be found at any point in the production line from steelmaking to finished product. Because of the elongation during rolling, cracks formed in the early stage of processing will elongate during the later. Cracks can be detected with the naked eye or at a low magnification after the surface of the wire rod has been chemically or mechanically descaled. Often, eddy-current equipments are used in-line to detect surface cracks.
Scratches are depressions, always running longitudinally along the bar or wire. They are caused by physical contact with a sharp object such as poorly machined, worn or broken guides. Scratches can be detected by the naked eye or at a low magnification, even in the scaled condition.

### 3.3.2. Fins and laps

Due to improper roll adjustment, overfilling may occur in one pass. Then in the next pass, the overfilled region passes a roll-groove bottom, folds and is rolled into the surface trapping a double oxide layer just beneath the rod surface. The folded material is recognised as “fins” or “laps” and the appearance is shown in Fig. 8. In a continuous mill, laps cannot be avoided at the ends of the coils which then have to be cut and recycled. The reason for forming laps is that the wire is simultaneously gripped by many rolls and normally stretched. At the ends, the stretching disappears and the bar becomes thicker overfilling the roll gap with the formation of laps. However, laps can also be formed when the roll pass is not adequately filled or when the guides are badly aligned. Poorly filled parts of the cross section can then develop into laps in the next roll pass. Often, it is difficult to distinguish laps from defects of similar appearance like shells, scratches or scoring.
3.3.3. **Corner cracks**

Some forms of surface cracking are caused by a combination of limited ductility and high stress concentrations [9]. These cracks are transversely oriented, usually appearing on the corners of a billet but may extend appreciably along the sides as in Fig. 9. Many high-alloy steels have an inherent low ductility and are particularly prone to such corner cracks. Strict control of stock composition and reheating conditions can reduce the severity of corner cracking [10].

3.3.4. **Porosity**

The finishing rolling-speed for rolling wire rod has successively increased up to 100-140 m/s [11, 12]. Such a high rolling speed generates a high temperature rise and high strain rate in the wire rod in a short time. This causes a risk of partial melting at grain boundaries in the material leading to defect problems such as porosity, for instance. See Fig. 10.
3.4. **Defects from improper roll pass design**

During rolling strains and heat are accumulated which may result in the development of defects. Just as an improper roll pass design may initiate and increase the defect size during rolling, a proper design may reduce the defects, and in the best case, even eliminate them. A study of a diamond-square and a square-oval pass has shown, that the most efficient method for eliminating an artificial surface crack, is to design the roll pass for a material flow in the radial direction opening up the crack in the angular direction [13].
4. Materials

In the present thesis a common high speed steel, SS2722 (AISI/SAE M2) and an austenitic stainless steel, AISI 304L have been studied. The compositions are listed in Table 1. Admittedly, the exact composition of M2 was not known. As a result, a nominal composition is listed in the table for this material.

Table 1 Chemical composition of investigated steels in wt%. M2 from reference [14,15]

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Co</th>
<th>Cu</th>
<th>N</th>
<th>Nb</th>
<th>W</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>304L</td>
<td>0.02</td>
<td>0.4</td>
<td>1.2</td>
<td>0.03</td>
<td>0.003</td>
<td>18.3</td>
<td>9.6</td>
<td>0.34</td>
<td>0.27</td>
<td>0.30</td>
<td>0.02</td>
<td>0.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>0.85</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.2</td>
<td>5.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.3</td>
<td>2.0</td>
</tr>
</tbody>
</table>
5. Theoretical considerations
During rolling, the bars are elongated in the rolling direction and deformed in
the cross section keeping the total volume constant. Naturally, cracks may be
positioned in regions where the material is either strained or compressed in the
cross section resulting in different evolution of the cracks. It is thus necessary to
analyse the evolution of defects with respect to the geometrical shape change of
the cross section during rolling. The analyses will be described in the present
section. The first paragraph will cover surface defects whereas the second one
will cover a central, longitudinal cavity with a round cross section.

5.1. Evolution of surface defects
In order to scale the evolution of the crack depth with the corresponding
evolution of the cross section an “equivalent” crack depth, $c_i^{eq}$, was defined as:

$$c_i^{eq} = \frac{d_i}{d_0} = \frac{\text{Crack depth after pass } i}{\text{Original crack depth}}$$

(1)

In order to scale this quantity with the cross section evaluation, the evolution of
a round bar rolled in round grooves was considered. In such a case, the radius, $r$,
scales according to:

$$\frac{r_i}{r_0} = \sqrt{\frac{A_i}{A_0}}$$

(2)

where $A$ represents the cross section area of the bars. The subscripts indicate the
passes, $0$ for the entry bar and $i$ after pass $i$, respectively. The scaled quantity,
called “relative” crack depth was thus defined as:

$$c_i^{rel} = \frac{c_i^{eq}}{r_i/r_0} = c_i^{eq} \sqrt{\frac{A_0}{A_i}}$$

(3)

Admittedly, this relation is only perfectly valid for round bars, but the deviation
for the ovals is not so large, as discussed by Nordén and Jonsson [16]. An
illustration from their work is given in Fig. 11, where the dashed line indicates
the result of Eq. (2) whereas the solid line indicates the angular dependence of
$r_i/r_0$ as measured on an oval. In this case Eq. (2) scales the defects with 1.6
whereas the scaling should vary from 1.5 to 1.9, i.e. a deviation of maximum
$(1.9-1.6)/1.6 = 19\%$ is encountered.
5.2. Evolution of inner defects

In the present thesis an “equivalent defect widening” is defined for the central cavity as:

$$w_i^{eq} = \frac{w_i}{w_0}$$  \hspace{1cm} (4)

i.e. the width after pass “i” divided by the original width. Naturally, a similar definition can be used for an “equivalent bar widening”, $W_i^{eq}$. By taking their relation, the “relative defect widening” is defined as:

$$w_i^{rel} = \frac{w_i^{eq}}{W_i^{eq}} = \frac{w_i}{w_0} \cdot \frac{W_i}{W_0} = \frac{w_i}{w_0} \cdot \frac{W_i}{W_0}$$  \hspace{1cm} (5)

If this quantity is equal to one, the central cavity is reduced at the same rate as the bar, i.e. the geometry is purely scaled by a factor. The character of the defect is unchanged. However, if $w_i^{rel} > 1$, the defect is becoming more severe and if $w_i^{rel} < 1$, the defect is becoming less severe. Thus, the “relative defect widening” can be used to judge the evolution of the defect harm.

Naturally, similar relations can be defined for the height changes, but their analyses will be less important since the height is severely reduced already in the first pass.
Another aspect to analyse is the velocity increase of the bar as it passes the rolls in the block. The block is designed for a solid bar but was now used to roll a hollow bar having an additional freedom of deformation. It can reduce the cross sectional area of the central cavity altering the exit velocity compared to a solid bar. This alteration is a potential risk for the stability of the rolling process as the wire rod block is incapable of adjusting to it.

The continuity relation gives:

\[ (A_i - a_i) v_j = (A_{i+1} - a_{i+1}) v_{j+1} \]  

which can be rearranged to:

\[ v_{i+1} = v_i \frac{A_i - a_i}{A_{i+1} - a_{i+1}} \]

where \( A \) and \( a \) denote the cross sectional area of the bar and the cavity, respectively, and \( v \) denotes the velocity. However, since no velocity is measured it is not possible to recalculate the individual velocities between the different rolls. On the other hand, it is possible to calculate the relative velocity change in each pass using:

\[ \frac{v_{i+1} - v_i}{v_i} = \frac{A_i - a_i}{A_{i+1} - a_{i+1}} - 1 \]

With the result of this formula, it is possible to discuss the change in interstand stresses, for instance, as a result of the artificial defect.
6. Experimental techniques

6.1. Evaluation of surface cracks

The M2 high speed steel was used for investigating the evolution of artificial V-shaped, longitudinal surface cracks positioned at 0, 45 and 90° from the vertical axis. See Fig. 12. A total of 9 bars were prepared with artificial cracks and rolled in six passes in a false round-oval series. The bars were rotated between the passes as indicated in Fig. 12. Samples were cut from the rolled bars measuring the crack depth which was related to the deformation of the cross section according to Eq. (3). The results will be discussed in section 8.

<table>
<thead>
<tr>
<th>Pass</th>
<th>Entering cross section</th>
<th>Exiting cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,3,5</td>
<td><img src="image1" alt="Diagram 1" /></td>
<td><img src="image2" alt="Diagram 2" /></td>
</tr>
<tr>
<td>2,4,6</td>
<td><img src="image3" alt="Diagram 3" /></td>
<td><img src="image4" alt="Diagram 4" /></td>
</tr>
</tbody>
</table>

Fig. 12 Illustration of orientation of bars and position of cracks. Note that the bar is rotated between the passes.

6.2. Evaluation of inner defects

The AISI 304L steel was rolled down in 22 passes into a bar of 12.5 mm in diameter at Fagersta Stainless AB, Fagersta, Sweden. The experimental bar was collected just before it should have entered the wire rod block and was later cut into test bars of length 1200 mm. The bars were then prepared with a central and longitudinal, artificial cavity by cutting them 400 mm from one end and drilling a 4 mm in diameter and 50 mm long hole into both cut ends. Finally, the pieces were welded together and ground to produce a correct geometry of the welds.

One by one, the prepared bars were heated by resistance to 930±70°C and fed manually into the wire rod block, Fig. 5, set to produce a final exiting speed of 60 m/s in pass 8. By entering a guide after the first roll pair, the first bar was led out from the block and directly into a water-filled tube for rapid quenching. Then, the guide and tube were moved and positioned after the second roll pair in
order for the second bar to be lead out and water quenched after being rolled in pairs 1 and 2. Then, the guide and tubes were positioned after pair 3 allowing the third bar to pass pairs 1, 2 and 3 before water quenching, and so on. The process was repeated until bar number eight was quenched after passing the whole wire rod block. By the rapid water quenching, the grain structure was supposed to be preserved allowing it to be analysed after each pass in the block. In order to be able to characterise the original structure, an extra bar was heated and then directly water quenched without rolling.

After rolling, samples were cut from the quenched bars, ground and polished. For optical examination, the samples were etched in a mixture of 50 ml HCl, 5 ml HNO₃ and 50 ml H₂O at 55°C. This revealed the grain size of the samples after each pass. The width and height of the hole and the bar were measured directly in an optical microscope. The results will be discussed in section 8.
7. Numerical simulations

7.1. Material models

7.1.1. High speed steel AISI M2

M2 was modelled as an elastic-plastic isotropic hardening material obeying von Mises yield criterion. The yield stress was modelled according to Hensel and Spittel [17] with the following formulation:

\[
\sigma = \sigma_0 A_1 t^{mT} A_2 \varepsilon^{m_2} A_3 \varepsilon^{m_3}
\]

(9)

where \(\sigma, \varepsilon, \dot{\varepsilon}\) and \(T\) represent stress, strain, strain rate and temperature, respectively. The other symbols represent parameters listed in paper A.

7.1.2. Austenitic stainless steel AISI 304L

The material behaviour of the AISI 304L stainless steel is described by a simple material model based on dislocation density [18]. The effects of deformation hardening and dynamic recovery were included in the model whilst static recovery and recrystallization were not included. The flow stress, \(\sigma\), is related to the dislocation density, \(\rho\), strain rate, \(\dot{\varepsilon}\), and absolute temperature, \(T_k\), by the following equations:

\[
\sigma = \sigma_0 + \alpha G b \sqrt{\rho}
\]

(10)

\[
\frac{d \rho}{dt} = \frac{m \dot{\varepsilon}}{b L} - \Omega \rho^2
\]

(11)

\[
\Omega = \Omega_0 \dot{\varepsilon}^n \exp\left(-\frac{Q_\Omega}{RT_k}\right)
\]

(12)

where \(G, b\) and \(m\) are the shear modulus, the magnitude of the Burgers vector and the average Taylor factor, respectively. The parameters, \(\sigma_0, \alpha, L, \Omega_0, n\) and \(Q_\Omega\) are adjustable coefficients which can be evaluated from experimental flow curves for the current material. The values were directly taken from the same reference where the model was also used for an AISI 304L stainless steel. In this reference the model is also described in more detail.

7.2. FE-simulations

All FE-calculations were performed with MSC.Marc. The bars were modelled with eight node isoparametric brick elements with eight integration points. Due to symmetry, one quarter of the cross section was modelled to shorten computational time. The materials were modelled as elastic-plastic isotropic hardening materials and von Mises yield criterion was used. The rolls were
considered as rigid and where therefore modelled with surface elements of constant angular velocity and temperature. Friction was modelled using a shear stress factor of 0.6 in Paper A whereas a coulomb friction of 0.3 was used in Paper B.

For the surface cracks, two series of calculations were performed. In one series, real cracks were simulated whereas in the other series only node points under the surface were monitored during the rolling simulations. Thus, no cracks were present in the latter model.

For the wire rod block (paper B) four models were built, from one to four roll pairs. The behaviour of the metal during wire rod rolling was simulated in a thermo-mechanically coupled analysis. Because of computational difficulties, the numerical study was limited to the first four passes.
8. Summary of results

In this section, the most important results will be discussed briefly. More information is given in the appended papers.

8.1. Evolution of surface defects

In order to illustrate the angular dependence of the defect evaluation, the relative crack depth is plotted in a circular diagram where the radius represents $c_i^{rel}$ and the angle gives the orientation during rolling. See Fig. 13 and Fig. 14. For clarity, a circle of radius 1 is plotted in the same diagrams. It represents a pure geometrical scaling of the defects due to rolling. As seen, the calculated results show much less defect reduction than found experimentally whereas the difference is small between calculations with and without cracks.

Fig. 13  Relative crack depth after pass 1 at different orientations, 0, 45 and 90° from the vertical axis.

Fig. 14  Relative crack depth after pass 2 at different orientations, -90, -45 and 0° from the vertical axis.
The evolution of surface defects of different orientation during rolling is given in Fig. 15 to Fig. 17. As seen from Fig. 15, the FEM calculations without cracks show the same tendency as the experimental results, except for the last oval. The reason for the discrepancy is probably due to instability when rolling a false round bar. The FEM calculations with cracks show the same tendency as the other series, but with lower reduction of the defects.

![Graph showing relative crack depth evolution](image)

**Fig. 15** Relative crack depth evolution for an initial orientation of $0^\circ$ to the vertical axis. G and S indicate whether the crack is located in the groove or at the free side. The insert to the right illustrates the orientation of the crack.

Also in Fig. 16, the calculated results show smaller reduction than found experimentally. The difference between calculations and experiments are larger for this crack orientation, but the difference between the calculations is small. As before, instability occurs during rolling. In Fig. 16, it appears in the second oval.
Fig. 16  As in Fig. 15, but for an initial orientation of 45° to the vertical axis.

In Fig. 17 there are also large deviations between calculations and experiments. As before, the experimental results show a quicker reduction of the defects. In fact, the defects could not be found at all in the two last, false round passes.

Fig. 17  As in Fig. 15, but for an initial orientation of 90° to the vertical axis.

8.2.  Evolution of inner defects

The cross sections of the bars prepared with a central cavity are shown in Fig. 18. Two dotted circles are superimposed on the micrographs to show the
geometrical scaling of the original artificial defect. As seen, the defects reduce in size quicker than predicted by a pure geometrical scaling.

Fig. 18 Cross sections of hollow bars after each pass (a-h) in a round-oval series. The dotted inserts illustrate uniform shrinkage of the original cavity by geometrical scaling.
The relative size change of the defects, with respect to width and height, is shown in Fig. 19. As seen, the calculated and experimental results are in good agreement. The round passes appear to reduce the width of the cavity more effectively than the ovals as they tend to show lower values. In pass 6 (round) a deviation from the previous trend can be seen. This deviation is caused by the development of a Z-shape appearance of the cavity. See Fig. 18f. As also seen from Fig. 19, the height of the defect is effectively reduced in the first pass and is much less than the width of the cavity in all succeeding passes.

![Plot of Relative Size Change](image)

**Fig. 19** Relative size change of defect with respect to width and height. Eq. (5) is used for calculating the relative defect widening. A similar equation is used for the height changes.

In Fig. 20, the calculated and experimental profiles of the cross sections are compared. As seen, the experimental ovals show clear asymmetry with overfilling on the left. The rounds also show asymmetry with slight overfilling at the top and bottom. The strong asymmetry for the experimental ovals is probably caused by insufficient guiding of the entry bar or disturbances from the extra guide inserted after the roll gap to catch the rolled bar before entering the
The next roll gap. The calculated results, on the other hand, do not suffer from such problems.

The round profiles, Fig. 20b and Fig. 20d show excellent agreement between the calculated and experimental results. A slight overfilling is predicted, just as found experimentally. In Fig. 20b, the central cavity is well reproduced, whereas in Fig. 20d, it is too thin.

![Fig. 20 Experimental and predicted profiles of bar and cavity after pass 1-4.](image)

Two longitudinal cross sections are shown in Fig. 21. The left-hand series shows a section perpendicular to the first roll gap whereas the right-hand series shows a section parallel to the first roll gap, i.e. rotated 90° to the first series. Both sections show compression, widening and reopening of the central defect as it is rolled through the different passes on its way from the top to the bottom of the page. As seen, the deformation is concentrated along the sides of the cavity.
Fig. 21  Length sections though the rolled bar at pass 1-4 showing the effective strain in colour. For optimum contrast, each section has its own colour scale. Line drawings next to the sections illustrate the direction of deformation, either in the plane of the paper or perpendicular to it. Rolling direction, RD, is from top to bottom, as indicated by the arrows.

In Fig. 22, the relative velocity change is calculated from Eq. (8) using the experimental and calculated cross sections. As seen, the largest split between the curves for solid and hollow bars occurs in the first pass and is then reduced quickly in the following passes. Due to the alternating closing and opening of the central cavity, the curve for the hollow bar crosses the curve for the solid bar
between every pass. In the oval passes, the solid bar is increasing its relative speed more than the hollow one. In the round passes, the situation is reversed. Since the hollow bar increases its speed less than the solid bar, it will enter the second pass too slowly. When the second pair of rolls has gripped the bar, it will be held back by the first pair of rolls. Hence, the interstand stresses between pass 1 and 2 will be higher for the hollow bar than for the solid one. Between pass 2 and 3, on the other hand, the situation is reversed, as the velocity increase in pass 2 is higher for the hollow bar than for the solid.

It is satisfactory to see that there is good agreement between calculations and experiments.

![Graph](image-url)

**Fig. 22** Relative velocity change at pass 1-8 calculated from Eq. (8).
9. Conclusions
The short, general conclusions drawn from the work in the present thesis can be condensed to:

9.1. **Surface defects**
- Calculations show less reduction than found experimentally.
- Calculations with and without cracks give similar results.
- Calculations show both similar and deviating trends compared to the experiments.

9.2. **Inner defects**
- Calculations show less reduction than found experimentally.
- Calculations of relative size change show good agreement with experiments.
- Calculated profiles are in good agreement with experimental results for the rounds. The ovals have suffered from misalignment during rolling.
- Deformation is concentrated near the cavity.
- Calculated relative velocity change is in good agreement with experiments. The altered velocity gives altered interstand stresses as the block cannot adjust itself to local velocity changes due to cavities.
10. Suggestion of future work
The present work has studied two materials, M2 and 304L. The results are stimulating since it shows good agreement in some cases, but is also deviating in some cases. There is thus a need to understand how the calculations should be modified in order to reproduce the experimental results better. It is also necessary to apply the methods to other materials, like duplex stainless steels to see if similar results can be obtained as presented in the present thesis. Some suggestions for future activities are:

- Material models can be developed taking high strain rates into account as well as recrystallisation, grain size and grain growth.
- Defect evolution in other materials can be investigated.
- Effects of different rolling temperature and rolling velocity on the defect evolution.
- By calculations, it may be possible to optimise the pass series with respect to defect reduction.
References

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Appendix Papers A and B