Experimental Study on the Mechanism of Pinching in Cold-Rolling Processes

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Herein, an experimental investigation into the occurrence of “pinching” defects during cold-rolling of thin metal sheets is presented. Pinched strips are typically characterized by repetitive ripples and local ruptures, which can cause strip breaks. Even though pinches are a widely experienced phenomenon in both hot- and cold-rolling of steel strips, no previous studies are known that have investigated the underlying mechanism for pinching during continuous rolling processes. Therefore, a set of rolling experiments is performed in a single-stand pilot mill to create pinches by applying sudden perturbations in the process conditions. For the rolling settings chosen in the performed experiments, it is found that disruptions in the lubrication state are a powerful approach to induce shape defects, which develop as pinches. Herein, a first extensive description of the pinching mechanism is provided, as observed during the trials, by monitoring the strip’s behavior and analyzing the damaged sheets. It is shown that ripples in these pinched strips are the result of folds, which form in the roll bite. The folds originate from the waviness of the strip upstream of the bite, being created by nonuniform conditions over the width of the strip.

1. Introduction

During the last few decades, lower CO₂ emissions through weight reduction became a point of great interest, especially for the automotive industry. Advanced high-strength steel (AHSS) grades allow to reduce thickness of the finished components, while maintaining high mechanical performances. Therefore, steel producers need to meet an increasing demand for thin-gauge AHSS products. Already for current high-strength steels, cold-rolling of strips is a critical process, which often suffers from instabilities. During rolling of thin sheets, shape defects may occur. Shape defects are due to uneven elongation over the width of the strip, which may result in flatness defects. The most commonly known ones, among those listed by Roberts,[3] are center buckles and wavy edges, which occur at the exit side of the roll bite. Pinches are also widely experienced during rolling processes. When pinching occurs, surface marks, wrinkling, repetitive rippled areas, and local ruptures are observed, as shown in Figure 1. In the most catastrophic cases, the strips break completely. Furthermore, heavy pinching may damage the work rolls (WRs), or even the backup rolls (BR). Marks appearing on the rolls’ surface are transferred to the rolled sheet, heavily affecting the production, with considerable plant down time. Even pinches of low severity, that are inhomogeneous internal stresses, might be critical, as they can result in difficulties during further processes and, in some cases, in unacceptable defects in the final products.

Flatness defects in rolling have attracted the attention of many researchers. Shape defects have been mostly analyzed in relation with the geometry of the entry strip (profile) or the WRs (crown). Many studies have shown that during rolling, flatness defects typically appear in the strips, which are subjected to heterogeneous thickness reduction across the width. This can be caused by nonuniform strip profile, thermoelastic deformation of the rolls, or roll grinding crown and wear. Uneven elongations of longitudinal fibers can generate residual stresses in the strip at the exit of the roll bite. If residual stresses locally exceed the critical value for buckling, flatness defects occur in the outgoing strip. This general mechanism for flatness defects has been extensively examined in the literature, especially concerning center buckles and wavy edges. Song et al.[4] have demonstrated that for steel strips with large width-to-thickness ratio, the transverse thickness difference has a critical influence on the shape stability. Moazeni and Salimi[5] have identified the transversal flow of material as cause of uneven flow in the rolling direction. This causes nonuniform longitudinal stresses over the width of the strip, that can affect the final shape, especially for thin sheets.
Different modeling strategies have been adopted to represent shape defects in rolling. Uncoupled and coupled rolling models have been compared. The latter ones account for the plastic deformation of the strip, the elastic deformation of the rolls and the influence of post-buckling stress reorganization on the in-bite stresses. The effect of friction variation, both in rolling and transverse directions, on flatness defects has been investigated in several works. Specifically, Nakhoul et al. have shown that friction has an impact on the reduction profile: the rolling load, which depends on the friction, causes roll deformation, with an effect on the distribution of residual stresses. A number of works has been dedicated to the development of flatness control technologies for improvement of the rolling process. Good shape of the rolled strips is usually achieved by ensuring that the profile of the entry strip and the roll-gap distribution correspond to each other, hence eliminating transverse variation in strip reduction. This objective can be obtained by using complex online measurements systems and actuators, enabling dynamic roll-gap profile changes. The most common means for shape control are roll bending, shifting and tilting, differential cooling distribution, and roll profiles optimization. Nakhoul et al. based on the study of the impact of friction on the strip’s shape, have demonstrated that an optimal setting of the WR bending force should be chosen depending on the friction level. Wang et al. have investigated the efficiency of the roll bending actuator with the purpose of predicting flatness defects position. Based on the simulation results of a 3D finite element model of a six-high tandem mill, they have shown that more complex types of flatness defects, like quarter buckles, happen when the control features of the actuator do not match the entry strip’s profile. Such a result proves that many issues of shape control have not been solved yet, due to the complexity of applying flatness control technologies in tandem mills.

Very little has been reported about pinching, and most of the available literature concerns the problem of pinched tails. An example is shown in Figure 2a. Indeed, in tandem mills, pinching phenomena have been mostly observed in combination with snaking (strip sideward movements) during tailing out, when process conditions suddenly change as the strip leaves a previous stand. Kampmeijer and Mysore have developed an algorithm to detect pinching phenomena occurring during tailing out. This algorithm has been included in a software tool that analyzes the images obtained from a surface inspection system. Classification of pinched tails is based on the identification of the prominent feature of pinching, that is the appearance of a ripple-like shape. Kampmeijer et al. have identified the source of tail pinching in the curved configuration developed by the strip’s tail due to sideward movement. The latter is caused by level errors, that are misalignments of the WRs, as indicated by the measured difference in the roll force between the drive side (DS) and the operator side (OS). A solution to the problem of pinched tails is represented by improvement of strip tracking, as discussed by Hol et al. their work describes the implementation of a tilt controller, active during tailing out of the strip, to steer back the center line by adjusting the roll gap. However, lateral motion of the strip can occur also between the uncoiler and the first stand of a cold-rolling mill. This case has been studied by Tarnopolskaya et al. who have shown that lateral deviation of the strip at the entry of the roll bite under asymmetric rolling conditions (loading and geometry of the mill) remains small if the applied tension is sufficient to prevent strip buckling. In a later work, Tarnopolskaya et al. have introduced buckling in the model of lateral dynamics. Their modeling results have revealed that buckling changes the nature of the lateral dynamics of the strip, leading to increased lateral deviations and potential instability. Moreover, pinches are a very common issue also near the weld between two coils, as shown in Figure 2b. The conditions at the roll bite suddenly change, due to the geometrical discontinuity in the strip’s width at the notch. Hence, similarly to the case of tail pinching, this creates a disruption in the stationary process, which may result in defects.

Pinching phenomena may appear even during continuous rolling processes, as shown in Figure 1. Pinches may occur on any type of steel sheet, not being limited to a specific steel type. However, high-strength steels are more prone to develop pinching due to the low thickness of the rolled sheets. Furthermore, these defects have been reported for all steel-rolling operations, during hot-rolling as well as during cold- and temper-rolling, and for different mill configurations. They are not confined to a limited set of process conditions and the speed at which pinching occurs also varies widely. Moreover, occurrence of pinching cannot be related to a specific
type of lubrication, being possible either without lubrication (as in hot rolling), or with lubrication (both with emulsion and direct application [DA]). These defects do not occur specifically at the middle or at the edges of the strip and they are, in general, not aligned with the rolling direction. The size of pinching defects can also vary in a wide range. This suggests that the mechanism of pinching is more elusive than that of shape defects alone. Therefore, the relation between shape defects and pinching requires a fundamental understanding.

Although pinching is a commonly experienced problem in industrial mills, according to the author’s knowledge, the nature of process disruptions leading to pinches during a continuous rolling process has never been investigated, leaving a gap in the research field. To prevent pinches and obtain stable rolling mill operation, a predictive analysis of these phenomena is needed. The development of a simulation tool requires a preliminary study. Based on this purpose, the paper focuses on an in-depth experimental investigation and analysis of pinching phenomena in cold-rolling processes. A set of rolling experiments was performed in a single-stand pilot mill. The mill configurations and the properties of the rolled material are described in Section 2. WR’s crown (convex or concave) and sudden changes in the lubrication, rolling forces, strip tension forces, and stand configuration (bending and tilting) have been tested as possible causes for pinches. A description of the most relevant experiments is given in Section 3. Observations made during the tests which resulted in pinching are presented in Section 4. The underlying mechanism which leads to the formation of pinching defects during the trials is described in Section 5. Finally, the main findings of this study are summarized in Section 6.

2. Experimental Section

The unpredictable occurrence of pinching posed difficulties to experimental investigation, especially during the production process. Tandem cold-rolling was a multi-variable complex process. Therefore, a more simple rolling system was considered to investigate the mechanism of pinching. A set of rolling experiments was performed using a single-stand pilot mill, represented in Figure 3, where both two-high and four-high configurations could be set up. Moreover, rolling speed, rolling forces, strip tension forces, and lubrication conditions could be set to be representative of industrial applications. Additionally, the pilot mill could be easily equipped with cameras and lighting systems to be used for imaging, both upstream and downstream of the roll bite.

During the performed tests, the DA lubrication unit was used. As shown in Figure 3, it provided pure oil to lubricate the strip at the entry side of the stand. The lubricant was sprayed on both the top and bottom surfaces of the strip. An industrial rolling oil, Rolkleen DR 1832, was used for the tests.

Different WR profiles were used: cylindrical, convex, and concave. The latter ones were characterized by crown of ±0.04 mm, measured in the middle of the section (on the diameter). Moreover, in the four-high configuration, which was most common in industrial cold-rolling mills, actuators for bending and tilting could be used. The amount of tilting specified in this work represented the difference in the vertical position of the BRs between DS and OS, measured at the location of the bearings. According to the convention adopted in this paper, a positive value means tilting applied toward the OS.

The dimensions, Rockwell C Hardness (HRC) and roughness of the WRs and the BRs (BR) are given in Table 1.

A thin sheet of typical low-carbon packaging steel was used for the tests. The rolled coil, 180 mm wide and 0.255 mm thick, was in continuous annealed state. The true stress–strain curves produced from a tensile test are plotted in Figure 4. The test was performed on samples taken at 0°, 90°, and 45° with respect to the rolling direction. The three curves showed identical mechanical properties of the material in all the directions. This was an indication of isotropic behaviour, as expected for annealed material.

The process was monitored by using some online measured data, that were rolling force, entry and exit strip tension forces, and pinching

Table 1. Features of work rolls (WR) and backup rolls (BR).

<table>
<thead>
<tr>
<th>Rolls</th>
<th>Width [mm]</th>
<th>Diameter [mm]</th>
<th>Hardness [HRC]</th>
<th>Roughness (Ra) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR for two-high configuration</td>
<td>360.00</td>
<td>397.00</td>
<td>55</td>
<td>0.30</td>
</tr>
<tr>
<td>WR for four-high configuration</td>
<td>360.00</td>
<td>136.70</td>
<td>55</td>
<td>0.32</td>
</tr>
<tr>
<td>BR for four-high configuration</td>
<td>360.00</td>
<td>324.12</td>
<td>55</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Figure 3. Schematic representation of the single-stand pilot mill.
thickness, and velocity of the strip. The tension forces were measured by tensiometer rolls, which were located at 2.6 and 2.0 m from the roll gap, respectively, at the entry and exit sides. The strip’s thickness was measured by thickness gauges placed at 1.1 and 0.9 m from the roll gap, respectively, at the entry and exit sides. In this setup, the DA unit was between the tensiometer roll and the thickness gauge, at a distance of about 2.4 m from the roll gap. However, local variations of tension forces, thickness, and velocity could not be captured by the mill’s measurements system. Indeed, the tension and strip’s velocity were simply average values over the width, while the thickness was measured only at the middle of the strip. Therefore, to investigate the effect of disruptions on the strip’s behaviour, images were captured by cameras installed upstream and downstream of the stand.

3. Rolling Experiments

A number of rolling experiments were performed in Tata Steel (IJmuiden) using the single-stand pilot mill depicted in Figure 5. Several rolling settings have been chosen for this study: lubrication, rolling force, strip tension forces and, for the four-high configuration, bending and tilting. During the tests, disruptions were created by changing one of these parameters, inducing the system to leave the stationary state. Furthermore, in some trials, disruptions have been applied in combination with tilting (misalignment of the WRs), which is known to be related to tail pinching due to the strip’s sideward movement. In some tests, pinches were observed, either in a mild or a heavy form. Generally, mild pinching is characterized by mild waviness appearing upstream of the roll bite and surface marks (lines and stains) on the outgoing strip; heavy pinching is featured by heavy waviness upstream, eventually associated with the strip’s lateral movement, while surface marks are accompanied by repetitive ripples and, sometimes, tears in the outgoing strip. In the most severe pinching events, the strips broke apart. In some trials, other types of flatness defects (e.g., wavy edges) were generated, without pinches; in other tests, pinching occurred in combination with wavy edges. Finally, some experiments did not produce any flatness defect. The complete overview of the performed tests is given in Appendix. The most relevant outcomes of the rolling experiments are resented in this section.

3.1. Disruptions of the Lubrication

Changes in the lubrication state were created, either starting the process with lubrication and then switching it off (DA on → off), or starting the process without lubrication and then switching it on (DA off → on). These tests were performed for different levels of the rolling force and the entry and exit tension forces. Furthermore, the case of asymmetric lubrication between top and bottom of the strip was tested, by opening or closing either the top or bottom nozzles of the DA unit. The process settings of these trials are summarized in Table A1 included in Appendix.

The most relevant outcome of these tests is that changes in the lubrication state can potentially cause pinching. Pinching defects were reported when lubrication was started or interrupted while rolling. The observed phenomena became more severe when there was an applied tilting in the position of the WRs. Asymmetry of lubrication between top and bottom was found to be not related to pinches. Similar tests were performed in two-high configuration, either with convex or concave WRs, and disruptions in the lubrication state. These trials are summarized in Table A2 and A3 of Appendix. Changes in the lubrication state have produced pinching defects, sometimes in combination with wavy edges in the case of rolling with concave rolls, high rolling force, and low tension forces.

3.2. Disruptions of the Rolling Force and Tension Forces

Furthermore, tests have been performed in which either the rolling force or the tension forces were changed while rolling, as summarized in Table A4 given in Appendix. These tests have been executed both with and without lubrication, with no applied tilting, and for different levels of the rolling force and the entry
and exit tension forces. Pinches were not observed, but for high rolling forces, due to the bending of the WRs, wavy edges were observed, when the applied tension forces were kept low. However, pinches did not occur in combination with wavy edges. Similar tests were performed also with convex and concave WRs. As shown by the summary reported in Appendix (Table A5 and A6), pinches did not occur.

### 3.3. Bending and Tilting in the Four-High Configuration

Tilting and bending, which are often used as actuators for shape control in industrial mills, have been also analyzed in relation with the occurrence of pinching.

In the four-high mill configuration with cylindrical rolls, tests have been performed introducing rolls’ tilting, either toward DS or OS. These rolling experiments have been executed both with and without lubrication. The process settings and observations are summarized in Table A7 provided in Appendix. The same amount of tilting was applied toward OS and DS, producing the same results. Wavy edges have been detected on the strips rolled with tilting and in the absence of lubrication. Specifically, the outgoing strip exhibited waviness at the side of the applied tilting. An interesting outcome was given by the tests in which tilting was applied in combination with lubrication. These trials resulted in wavy edges and heavy pinching, contrary to rolling without lubrication, where no pinching occurred. Pinching defects were observed also when rolling at a lower speed (1 ms\(^{-1}\) instead of 2 ms\(^{-1}\)). Finally, tests have been performed in the four-high configuration in which the bending pressure has been increased while rolling. These tests, summarized in Table A8 of the Appendix, did not show any flatness defect.

### 4. Results

The core findings for the set of rolling experiments are presented in this section. The results of some of the performed tests are evaluated. The outcomes of these tests represent the most significant contribution of this experimental work to the posed research questions.

Tests 1, 2, and 3 analyzed in the following show the influence of lubrication on the occurrence of pinching phenomena. These three trials were performed with two-high configuration and cylindrical rolls. In tests 1 and 2, the DA unit has been switched off while rolling. The difference between these two tests is that in the latter the WRs were misaligned, due to an applied tilting. This resulted in more severe defects (heavy pinching) for test 2, compared to test 1 (mild pinching). In test 3, the DA unit has been switched on while rolling. This operation induced heavy pinching phenomena.

In test 4, lubrication also played a role in the occurrence of pinching. This trial was executed with four-high configuration and cylindrical rolls. In this case, there was not a direct intervention on the lubrication, as for tests 1, 2, and 3. The applied perturbation consisted in tilting the WRs, toward DS and OS, while rolling. The presence of lubricant made the process sensitive to pinches, which occurred, this time, along with wavy edges.

For the evaluated tests, the effect of disruption is analyzed, based on the process data and the strip’s behaviour, both upstream and downstream of the roll bite.

### 4.1. Test 1

The process settings for this test are summarized in Table 2, where \(F\) is the total rolling force (summation of the forces applied at DS and OS), \(H\) indicates the entry thickness, \(h\) represents the exit thickness (after reduction), \(V_R\) is the rolling speed, \(V\) is the entry strip’s velocity, \(v\) is the exit strip’s velocity, \(T\) is the entry tension force, and \(t\) is the exit tension force.

Disruptions in the lubrication state were created (DA on \(\rightarrow\) off), resulting in a change of the friction coefficient during the process. Rolling of thin strips is significantly affected by the friction coefficient, as clearly indicated by variations in the signals of tension forces, thickness, and strip’s velocity, as shown in Figure 6. On the horizontal axis, a relative time is used: at Time 0 s, the DA unit was switched off. Considering the strip’s entry velocity (1.49 ms\(^{-1}\)) and the distance between the DA unit and the roll gap (2.4 m), the time distance between operating the DA unit and the roll gap is of about 1.61 s. At Time 5.5 s, a fast stop is applied by the control system to interrupt the process, since the rolling forces reach a too high value, as shown in Figure 6a. As consequence of stopping the lubrication, fluctuations in the signals of the entry and exit tension forces, as measured by the tensiometer rolls, are observed (Figure 6b). These fluctuations have been encountered in the signals of all the reported pinching cases. Figure 6c shows an increase of the exit thickness over time. Less strip thickness reduction is a direct consequence of increasing the friction coefficient. Figure 6d shows how the strip’s velocity changes due to the disruption. When the DA unit is switched off, the strip’s velocity increases, both at the entry and exit sides.

The two consecutive entry side camera frames shown in Figure 7 highlight what happens in the case of mild pinching. Once the DA unit is switched off, the roll gap does not become uniformly dry, since residuals of lubricant are still present on the strip. In Figure 7a, a small droplet of oil is clearly visible near the OS edge of the strip. The roll surface appears partly shiny and partly dull, as consequence of uneven lubrication in the roll gap. Thereafter, a mild waviness occurs on the strip upstream of the roll bite, as shown in Figure 7b. The ruler displayed below each frame helps to track changes in the strip’s position (sideward movement). During this test, the mild pinching phenomena are not associated with any visible lateral displacement of the strip in the roll bite. In combination with the waviness appearing upstream, frames captured by the camera at the exit of the roll gap show a nonuniform finish of the strip’s surface, as it can be seen in Figure 8. The strip, before the perturbation, has a uniform dull finish, as shown by Figure 8a. Later, once the DA

<table>
<thead>
<tr>
<th>(F) [kN]</th>
<th>(H) [mm]</th>
<th>(h) [mm]</th>
<th>(V_R) [ms(^{-1})]</th>
<th>(V) [ms(^{-1})]</th>
<th>(v) [ms(^{-1})]</th>
<th>(T) [kN]</th>
<th>(t) [kN]</th>
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</table>
unit has been switched off, the surface appears partly shiny and partly dull, as visible in Figure 8b. Moreover, the dull regions appear as repetitive stains on the strip’s surface, being aligned with the rolling direction. The stains are often accompanied by dull marks and tears, as shown in Figure 9.

4.2. Test 2

The process settings for this test are summarized in Table 3. As in test 1, disruptions in the lubrication state were created (DA on → off), resulting in a change of the friction coefficient during the
Furthermore, this test was conducted with a misalignment of the WRs, that is an applied tilting of \( \frac{C}{O} 0.3 \text{ mm} \).

After the DA unit has been switched off, oscillations in the entry and exit tension forces and increase of the entry and exit strip's velocity were recorded, similarly to what was shown for test 1. 

Figure 10 shows two consecutive frames captured by the entry side camera. In Figure 10a, a residual of oil appears on the strip's surface, as it has been observed for test 1. Compared to the latter, the pinching phenomena are certainly more remarkable. The different appearance of the roll surface, partly shiny and partly dull, is more notable. Moreover, disruptions in the lubrication state result in longer waves in the ingoing strip. The waviness in the strip at the entry side of the roll gap is not the only relevant aspect of the strip's behavior. Differently from test 1, it is observed that the strip has slightly moved sideways. After the DA unit is switched off, the appearance of the rolled strip changes. Once more regions of the strip's surface with dull finish (surface stains) and regions with a brighter finish can be seen in Figure 11b. Surface dull marks and tears of the type shown in Figure 9 were observed also for this trial. The slight sideward movement of the strip to the DS can be noticed also by looking at the exit camera frames.

### 4.3. Test 3

The process settings for this test are summarized in Table 4. These are similar to those of test 2, with the difference that in test 3 the process was started without any lubrication and, while rolling, the DA unit has been switched on. As in test 2, the test was conducted with a tilting of the WRs of \( \frac{C}{O} 0.3 \text{ mm} \).

The heavy pinching produced in this test has been a catastrophic event, ending with the complete strip's break.

Table 3. Process settings for test 2.

<table>
<thead>
<tr>
<th>( F ) [kN]</th>
<th>( H ) [mm]</th>
<th>( h ) [mm]</th>
<th>( V_e ) [ms(^{-1})]</th>
<th>( V ) [ms(^{-1})]</th>
<th>( \nu ) [ms(^{-1})]</th>
<th>( T ) [kN]</th>
<th>( t ) [kN]</th>
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</thead>
<tbody>
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<td>2.05</td>
<td>4.5</td>
<td>5.5</td>
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</tbody>
</table>

Figure 9. Surface stain, dull marks, and tears on the strip's surface in test 1 (dimensions: 625 mm by 180 mm).

Figure 10. Entry side camera frames of test 2: a) uneven lubrication; b) waviness.
Figure 12. Entry side camera frames of test 3: (a) uneven lubrication; (b) waviness.

Table 4. Process settings for test 3.

<table>
<thead>
<tr>
<th>F [kN]</th>
<th>H [mm]</th>
<th>h [mm]</th>
<th>$V_x$ [ms$^{-1}$]</th>
<th>$V$ [ms$^{-1}$]</th>
<th>$V$ [ms$^{-1}$]</th>
<th>T [kN]</th>
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<td>1.991</td>
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5. Discussions

The results of the rolling tests lead to some considerations on the mechanism of pinching, in relation to the process settings tested in this experimental work.

As previously mentioned, the general mechanism for flatness defects described in previous research works does not explain how pinches develop during rolling and the relation between shape defects and pinching phenomena. The performed rolling experiments show how pinching occurs due to shape problems induced by disruptions in the stationary process. The pinching cases encountered during the trials happened in combination with wavy edges, as well as without wavy edges. Hence, even though flatness defects and pinching have a common source, that is the shape defect, the formation mechanism is not necessarily the same. Furthermore, the tests have shown that, for the chosen rolling settings, a nongeometrical cause, that is uneven lubrication, can be a source of shape defects that lead to pinching. Once the lubricant distributes nonuniformly over the width of the strip, the conditions at the roll bite suddenly change. The
most distinct response to these disruptions is represented by large fluctuations in the signals of the entry and exit tension forces, as observed for all the pinching cases. Moreover, also the strip’s reduction, entry and exit velocities are noticeably affected by the disruption in the lubrication conditions.

The effects of uneven lubrication can be explained in more detail, taking as reference the results of test 1 presented in the previous section. When the DA unit is switched off, causing nonuniform distribution of lubricant in the bite, the friction coefficient locally increases. There are two main effects of this local change: 1) Less reduction takes place, as indicated by the higher exit thickness shown in Figure 6c, with a consequent increase of the entry speed, as it can be seen in Figure 6d; 2) The neutral point is shifted closer to the entry plane, also with a consequent increase of the entry and exit speed, as it can be seen in Figure 6d.

The second effect is a known one. According to Roberts,[1] in normal rolling conditions, with good lubrication over the entire strip’s width, the neutral point is typically closer to the exit plane than the entry one. In contrast, when a poor lubricant is used, the neutral point moves toward the entry plane. In those regions of the strip’s width where the two effects indicated earlier take place, due to the higher entry speed, the stress locally increases upstream of the roll bite, resulting in shape defects. With a constant total tension force, a local increase of stress must result in a local decrease of stress somewhere else over the strip’s width. Local compressive stresses of sufficient magnitude will trigger waviness upstream of the roll bite. Indeed, during the trials, it has been found that pinching originated from waviness of the strip, at the entry side of the roll bite. This waviness, which is in general not aligned with the rolling direction, as for wavy edges and center buckles, has been clearly shown in Figure 7b for test 1, Figure 10b for test 2, Figure 12b for test 3, and Figure 13b for test 4. Another important consequence of the uneven strip velocity, at the exit side of the roll gap, is the development of local high tensile stresses, which can cause tears in the outgoing strip, as shown in Figure 9 for test 1.

Additionally, shifting of the neutral point can be related to the characteristic appearance of the pinched strip’s surface at the exit of the roll bite, with both matt and bright areas, as shown in Figure 8b and 11b. It is known that a correlation exists between the appearance of the surface of the rolled strip and the friction coefficient in the roll gap, as explained by Roberts.[1] Indeed, the reflectivity increases as the effective coefficient of friction increases. Buffing of the strip’s surface is enhanced by slippage of the strip with respect to the rolls, behind the neutral point, where the strip velocity is higher than the rolls’ peripheral velocity. In case of good lubrication, the neutral point is close to the exit plane, hence little slippage of the strip with respect to the rolls occurs after the neutral point and, consequently, there is very little buffing of the surface. This results in a dull or matt finish of the strip surface. In contrast, for poorly lubricated conditions, the neutral point moves toward the entry plane and the slip of the rolled strip with respect to the rolls increases, resulting in more buffing and a more shiny strip’s surface.

Moreover, some tests have also demonstrated that misalignment of the WRs has an effect on pinching phenomena, which become more severe, as in test 2 compared to test 1. When tilting is applied, the strip moves sideward. Hence, even in a continuous
rolling process, pinching appears to be sensitive to snaking, like during tailing out, as reported in the work of Kampmeijer et al.\textsuperscript{[15]}

For all the pinching cases reported during the trials, the morphology of defects is very well comparable with those encountered in industrial mills. A sample taken from the strip of test 2 is analyzed, to show the main common features of a pinched strip. Figure 15 shows part of the pinched strip, where a series of ripples, strip marking lines, surface stains, dull marks, and tears can be observed. As typical of pinched strips, the repetitive ripples are slightly curved with respect to the rolling direction and cleaved by dark lines. The latter indicate local ruptures occurring through the rippled regions. Furthermore, the position of dull marks and tears over the strip’s width is always quite aligned with the ripples.

Based on the pinching phenomena observed during the tests, ripples with short wavelengths can be identified as the prominent feature of a pinched strip. A sample has been sectioned in the point where the ripple initiates, as shown in Figure 16. The strip’s structure has been analyzed by looking at the cross section, transverse to the rolling direction. The image captured with an optical microscope clearly reveals the occurrence of a three-layer structure.

Chemical etching was used to highlight the microstructure in the defect zone. The shape of the grains is different between the area of defect and the remaining cross section, as shown in Figure 17a,b, respectively. In the latter, the grains have a round shape, while in the former, they appear flat and elongated. Modification in the grains shape indicates that the strip has locally undergone a higher thickness reduction. This demonstrates that the three-layer structure is not due to cracks in the material, but due to a fold. Hence, the ripples visible on the...
strip’s surface are points where the strip has folded in the roll bite. This happens when the buckles occurring upstream of the roll gap pass through the WRs, toppling on the side. Similar analyses were performed on more pinched strips. The results of microscopy always revealed the change of the grains shape and the presence of a fold in the cross sections of the ripples.

Finally, a map of defects which typically characterizes pinched strip can be defined, based on all the observations made during this experimental investigation. The appearance of these complex defects is schematically represented in Figure 18. The image shows how pinching defects typically develop on the strip, with respect to the rolling direction.

6. Conclusions

Cold-rolling experiments have been performed to learn about the mechanism of pinching and its sensitivity to several parameters, for specific process settings. The main conclusions that can be drawn from this study are summarized in the following.

1) Pinches can be created in a single-stand pilot mill and the observed defects are comparable with those reported in industrial rolling processes. Therefore, the pilot mill can be regarded as a useful tool to create and analyze pinching phenomena.

2) Lubrication has been identified as a nongeometrical source of shape defects that, under certain conditions, develop as pinching.

3) Disruptions in the lubrication state lead to uneven thickness reduction over the strip’s width, which results in inhomogeneous stress distribution and waviness that can evolve as pinches.

4) Among all the observed defects, ripples are the main feature in the produced pinched strips.

5) Analysis of cross sections of rippled regions has shown the formation of folds in the transverse direction. Folds are considered the evidence of an underlying mechanism for pinches during the trials, that can be summarized as follows:

   a) sudden perturbations in the conditions at the roll bite can cause uneven thickness reduction and, consequently, nonuniform velocity over the strip’s width;

   b) nonuniform longitudinal stress distribution upstream of the roll gap is induced;

   c) locally compressive stresses are the source of buckling at the entry side of the roll bite; and as these buckles pass through the rolls, folds develop.

6) The severity of pinching defects is sensitive to misalignment of the WRs, for which pinches occur in combination with strip’s sideward movements.

7) Other defects, like nonuniform surface finish, surface stains, dull marks, and tears have been identified also as common features on the pinched strips produced in the tests.

8) Alternation of regions of dull and bright finish on the strip’s surface can be related to shifting of the neutral point, due to the uneven lubrication.

Appendix

This Appendix contains a summary of the performed rolling tests. In the tables below, $F$ is the total rolling force (summation of the forces applied at the drive side [DS] and the operator side [OS]), $T$ is the entry tension force, $t$ is the exit tension force, and $V_R$ is the stand rotational speed.

Table A1. Performed rolling tests in two-high configuration with cylindrical rolls and changes in the lubrication state.

<table>
<thead>
<tr>
<th>Analyzed test</th>
<th>$F$ [kN]</th>
<th>$T$ [kN]</th>
<th>$t$ [kN]</th>
<th>$V_R$ [ms$^{-1}$]</th>
<th>Perturbation (DA)</th>
<th>Tilting</th>
<th>Defect observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>550</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>on $\rightarrow$ off</td>
<td>None</td>
<td>Mild pinch</td>
</tr>
<tr>
<td>Test 2</td>
<td>420</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>on $\rightarrow$ off</td>
<td>$-0.3$ mm</td>
<td>Heavy pinch</td>
</tr>
<tr>
<td>Test 3</td>
<td>420</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>off $\rightarrow$ on</td>
<td>$-0.3$ mm</td>
<td>Heavy pinch</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>off $\rightarrow$ on</td>
<td>$-0.3$ mm</td>
<td>Heavy pinch</td>
</tr>
</tbody>
</table>
Table A2. Performed rolling tests in two-high configuration with convex rolls and changes in the lubrication state.

<table>
<thead>
<tr>
<th>F [kN]</th>
<th>T [kN]</th>
<th>t [kN]</th>
<th>V_R [ms⁻¹]</th>
<th>Perturbation (DA)</th>
<th>Tilting</th>
<th>Defect observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>on → off</td>
<td>None</td>
<td>Mild pinch</td>
</tr>
<tr>
<td>450</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>off → on</td>
<td>None</td>
<td>Heavy pinch</td>
</tr>
</tbody>
</table>

Table A3. Performed rolling tests in two-high configuration with concave rolls and changes in the lubrication state.

<table>
<thead>
<tr>
<th>F [kN]</th>
<th>T [kN]</th>
<th>t [kN]</th>
<th>V_R [ms⁻¹]</th>
<th>Perturbation (DA)</th>
<th>Tilting</th>
<th>Defect observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>on → off</td>
<td>None</td>
<td>Mild pinch</td>
</tr>
<tr>
<td>450</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>off → on</td>
<td>None</td>
<td>Heavy pinch</td>
</tr>
<tr>
<td>1000</td>
<td>1.0</td>
<td>1.0</td>
<td>2.00</td>
<td>off → on</td>
<td>None</td>
<td>Heavy pinch</td>
</tr>
</tbody>
</table>

Table A4. Performed rolling tests in two-high configuration with cylindrical rolls and changes in the rolling force or tensions.

<table>
<thead>
<tr>
<th>F [kN]</th>
<th>T [kN]</th>
<th>t [kN]</th>
<th>V_R [ms⁻¹]</th>
<th>Perturbation</th>
<th>DA unit</th>
<th>Defect observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>F → 450 kN</td>
<td>On</td>
<td>None</td>
</tr>
<tr>
<td>250</td>
<td>5.5</td>
<td>6.5</td>
<td>2.00</td>
<td>F → 850 kN</td>
<td>On</td>
<td>None</td>
</tr>
<tr>
<td>350</td>
<td>6.5</td>
<td>7.5</td>
<td>2.00</td>
<td>F → 850 kN</td>
<td>Off</td>
<td>Wavy edges</td>
</tr>
<tr>
<td>250</td>
<td>5.5</td>
<td>6.5</td>
<td>2.00</td>
<td>F → 850 kN</td>
<td>Off</td>
<td>None</td>
</tr>
<tr>
<td>350</td>
<td>6.5</td>
<td>7.5</td>
<td>2.00</td>
<td>F → 850 kN</td>
<td>Off</td>
<td>None</td>
</tr>
<tr>
<td>650</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>T → 6.5, t → 7.5 kN</td>
<td>On</td>
<td>None</td>
</tr>
<tr>
<td>650</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>T → 6.5, t → 7.5 kN</td>
<td>Off</td>
<td>None</td>
</tr>
</tbody>
</table>

Table A5. Performed rolling tests in two-high configuration with convex rolls and changes in the rolling force or tensions.

<table>
<thead>
<tr>
<th>F [kN]</th>
<th>T [kN]</th>
<th>t [kN]</th>
<th>V_R [ms⁻¹]</th>
<th>Perturbation</th>
<th>DA unit</th>
<th>Defect observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>F → 1000 kN</td>
<td>Off</td>
<td>None</td>
</tr>
<tr>
<td>250</td>
<td>5.5</td>
<td>6.5</td>
<td>2.00</td>
<td>F → 1000 kN</td>
<td>Off</td>
<td>None</td>
</tr>
<tr>
<td>250</td>
<td>6.5</td>
<td>7.5</td>
<td>2.00</td>
<td>F → 1000 kN</td>
<td>Off</td>
<td>None</td>
</tr>
<tr>
<td>250</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>F → 1000 kN</td>
<td>On</td>
<td>None</td>
</tr>
<tr>
<td>250</td>
<td>5.5</td>
<td>6.5</td>
<td>2.00</td>
<td>F → 1000 kN</td>
<td>On</td>
<td>None</td>
</tr>
<tr>
<td>250</td>
<td>6.5</td>
<td>7.5</td>
<td>2.00</td>
<td>F → 1000 kN</td>
<td>On</td>
<td>None</td>
</tr>
<tr>
<td>450</td>
<td>5.5</td>
<td>7.5</td>
<td>2.00</td>
<td>T → 2.5 kN</td>
<td>On</td>
<td>None</td>
</tr>
<tr>
<td>450</td>
<td>5.5</td>
<td>7.5</td>
<td>2.00</td>
<td>T → 6.5 kN</td>
<td>On</td>
<td>None</td>
</tr>
</tbody>
</table>

Table A6. Performed rolling tests in two-high configuration with concave rolls and changes in the rolling force or tensions.

<table>
<thead>
<tr>
<th>F [kN]</th>
<th>T [kN]</th>
<th>t [kN]</th>
<th>V_R [ms⁻¹]</th>
<th>Perturbation</th>
<th>DA unit</th>
<th>Defect observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>F → 1000 kN</td>
<td>Off</td>
<td>None</td>
</tr>
<tr>
<td>250</td>
<td>5.5</td>
<td>6.5</td>
<td>2.00</td>
<td>F → 1000 kN</td>
<td>Off</td>
<td>None</td>
</tr>
<tr>
<td>250</td>
<td>6.5</td>
<td>7.5</td>
<td>2.00</td>
<td>F → 1000 kN</td>
<td>Off</td>
<td>None</td>
</tr>
<tr>
<td>250</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>F → 1000 kN</td>
<td>On</td>
<td>None</td>
</tr>
<tr>
<td>250</td>
<td>5.5</td>
<td>6.5</td>
<td>2.00</td>
<td>F → 1000 kN</td>
<td>On</td>
<td>None</td>
</tr>
<tr>
<td>250</td>
<td>6.5</td>
<td>7.5</td>
<td>2.00</td>
<td>F → 1000 kN</td>
<td>On</td>
<td>None</td>
</tr>
<tr>
<td>450</td>
<td>5.5</td>
<td>7.5</td>
<td>2.00</td>
<td>T → 2.5 kN</td>
<td>On</td>
<td>None</td>
</tr>
<tr>
<td>450</td>
<td>5.5</td>
<td>7.5</td>
<td>2.00</td>
<td>T → 6.5 kN</td>
<td>On</td>
<td>None</td>
</tr>
</tbody>
</table>
Acknowledgements

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

advanced high strength steel, buckling, flatness defect, shape defect, thin strip

Table A7. Performed rolling tests in four-high configuration with cylindrical rolls and rolls tilting.

<table>
<thead>
<tr>
<th>Analyzed test</th>
<th>$F$ [kN]</th>
<th>$T$ [kN]</th>
<th>$t$ [kN]</th>
<th>$V_R$ [ms$^{-1}$]</th>
<th>Perturbation (tilting)</th>
<th>DA unit</th>
<th>Defect observation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>450</td>
<td>4.5</td>
<td>5.5</td>
<td>1.00</td>
<td>$\pm 0.15$ mm</td>
<td>Off</td>
<td>Wavy edges</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>$\pm 0.15$ mm</td>
<td>Off</td>
<td>Wavy edges</td>
</tr>
<tr>
<td>Test 4</td>
<td>450</td>
<td>4.5</td>
<td>5.5</td>
<td>1.00</td>
<td>$\pm 0.15$ mm</td>
<td>On</td>
<td>Heavy pinch and wavy edges</td>
</tr>
</tbody>
</table>

Table A8. Performed rolling tests in four-high configuration with cylindrical rolls and rolls bending.

<table>
<thead>
<tr>
<th>$F$ [kN]</th>
<th>$T$ [kN]</th>
<th>$t$ [kN]</th>
<th>$V_R$ [ms$^{-1}$]</th>
<th>Perturbation (bending force)</th>
<th>DA unit</th>
<th>Defect observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>$P \rightarrow 150$ kN</td>
<td>Off</td>
<td>None</td>
</tr>
<tr>
<td>450</td>
<td>4.5</td>
<td>5.5</td>
<td>2.00</td>
<td>$P \rightarrow 150$ kN</td>
<td>Off</td>
<td>None</td>
</tr>
</tbody>
</table>


