Laminação Rolling
49º Seminário de Laminação - Processos e Produtos Laminados e Revestidos
49th Rolling Seminar - Processes, Rolled and Coated Products
ISSN 1983-4764

HOT ROLLING SURFACE QUALITY ISSUES[1]

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Abstract
Surface quality issues in hot rolled plate and coil structural steel is a challenge for every steel mill around the world. Proper process set up along with overall processing parameters must be satisfactorily implemented in order to minimize surface quality issues in hot rolled coil, plate and sheet steels. Surface quality issues may initiate from various steelmaking, casting, reheating, hot rolling and overall plate/coil handling sources. Because sources of surface quality issues can be numerous, often, the appropriate analysis and identification of the root causes is incorrect resulting in ineffective corrective actions. A proper understanding of the potential sources of surface quality issues, a proper investigative root cause analysis, and in many cases, a simple process of elimination result in the successful implementation of the proper corrective action. There are fundamental operational, process set up and metallurgical parameters that are universal regardless of steelmaking, casting, rolling and overall mill configuration that need to be understood and controlled to minimize surface quality issues. The interaction of these factors governs the resultant hot roll surface quality and mechanical properties. It is extremely important that the proper identification of surface quality issues is determined so that the proper corrective actions can be employed. This paper will focus on common hot rolling defect characteristics, proper identification of such defects, cause and effect relationships, and corrective actions. Examples of actual cases will be presented.
Keywords: Defect identification; Hot rolling; Root-cause analysis; Surface quality.

1 *Technical contribution to the 49th Rolling Seminar – Processes, Rolled and Coated Products, October, 22nd-25th, 2012, Vila Velha, ES, Brazil.*
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ISSN 1983-4764

1 INTRODUCTION

The demand for cost effective structural steel products by todays design engineers require proper alloy/processing design selection. Not only are the requirements related to achieving specific mechanical properties, but also surface quality requirements are becoming increasingly more demanding. Many of the cost effective designs require higher strength to reduce thickness (reduced costs), however with reduced thickness of the structural member removal of surface quality problems that further reduces thickness is no longer tolerable.
Surface quality defects can come directly from numerous steel production process sources. In addition, surface quality defects can be indirectly influenced by other sources such as alloy design, reheat furnace fuel source, improper slab dimension selection, etc. While as-cast slab quality has a major influence on final hot rolled plate/coil surface quality,(1) there are many reheating, hot rolling, cooling and handling processing points that influence final plate/coil surface quality. At the hot rolling mill, the reheating furnace operation and hot rolling mill can be the root cause of surface quality issues and/or poor mechanical properties including toughness. The inefficient and non-homogeneous heating of the steel before rolling is often one of the reasons for mechanical property rejects and diverts.
Proper identification of the final as-rolled defect involves an understanding of the cause-effect relationship between surface defects characteristics and process control parameters. Proper investigation characterizes the appearance, shape, size and sometimes chemistry of the as-rolled defect, thereby providing valuable information for identification of the cause-effect relationship. Development of this relationship governs the appropriate corrective action.
This paper focus on common hot rolling defect characteristics, the identification of its causes and possible corrective actions, some examples of actual cases will be presented.

2 HOT ROLLING INDUCED SURFACE QUALITY DEFECTS

Plate/coil related surface defects that are introduced during the reheating, rolling, cooling and handling processes in the production of structural plate and coil can be numerous. The most common hot rolling induced surface quality defects in typical order of frequency are as follows:

I. Rolled in
   a. Scale
   b. Steckel Mill Scale
   c. Foreign Debris
   d. Refractory (exogenous inclusions from furnace, ladle or tundish)
II. Scale formation from other sources
III. Mechanical handling scratches/gouges
IV. Edge defects
V. Head and tail cracks
VI. Alloy design resulting in longitudinal or transfer cracks
VII. Overheating/burning of the slab surface leading to rough surface, pits and possible cracks (both longitudinal, transverse and/or corners)

By far rolled in scale, foreign debris and refractory tends to be the largest and most frequently identified source of plate/coil surface quality issues.

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For example, if a Steckel mill is utilized, then head and tail scale pits from the Steckel rolling operation are a major yield loss/surface quality issue. In addition, overall scale formation, color, consistency, etc. is the second most common surface quality complaint. Edge defects due to over use of broadsiding/edging along with mechanical handling scratches/gouges would be the third highest frequency cause.
Surface cracks on the head and tail due to head/tail shape issues coupled with descaling practices would be the fourth most frequent cause.
Alloy design, primarily carbon, sulfur, copper and nickel can also have various effects on the final hot rolled surface quality.
Finally, overheating/burning in most of today's modern steel facilities is the least common surface quality issue, but can still exist for some mills and can exist if improper reheat furnace operation/maintenance is in use, especially in older generation furnaces and or poorly maintained newer generation furnaces.
This paper will focus on the rolled in type of defects as this is the most frequent class of defects faced during hot rolling operations.

2.1 Rolled in Scale

Rolled in scale is the number one surface quality issue that most structural plate/coil hot rolling facilities face. It comes mainly from reheating primary furnace scale. Secondary scale formation can also be rolled in during the rolling process, but the formation of the secondary scale can just be an artifact from remaining primary reheat furnace scale that never was adequately removed, this residual scale becomes a nucleation site for secondary scale formation.
Primary reheat furnace scale formation is driven by the steel chemistry, predominately carbon, silicon, copper, nickel, chromium and molybdenum coupled with the atmosphere in the furnace and furnace temperatures.
Higher carbon (>0.12%) creates a thicker and more sticky primary scale while lower silicon (<0.15%) creates a “flaky” scale. The solute elements of copper, nickel, chromium and molybdenum create a “tighter” primary scale with nickel producing a very tight scale that can be difficult to remove. These chemistry relationships to scale formation and thickness universally apply to plate, sheet and bar.
Reheat furnace atmosphere plays a critical role in scale formation as does temperature and time. Many of today's integrated steel plants utilize coke oven gas from the Coke Plant and/or Blast Furnace as either the only fuel source for the reheat furnace or in a blended form with natural gas.
While this seems very prudent and economically correct, there are negative considerations as those gases have various levels of impurities that depend on the quality of the coke and iron ore purchased. This is translated in variations on the quality of the waste gases in the re-heating furnace atmosphere that cannot be controlled, resulting in variations on the scale quality.
The impurity that may cause the biggest problem with scale formation during reheating is the sulfur content of those waste gases. The sulfur forms SO_2 during combustion, making the scale difficult to remove during primary descaling. Increasing temperature (>1200 °C) and/or time (> 2 hours of exposure at temperatures higher than 1100°C) of the slab further aggravates the situation, such slabs tend to have more severe primary reheat furnace scale issues. Natural gas, if the sulfur content is high, can also cause similar problems.
Examples of slabs showing residual primary reheat furnace scale after high pressure primary descaling along with secondary scale nucleation after rough rolling can be seen in Figure 1.

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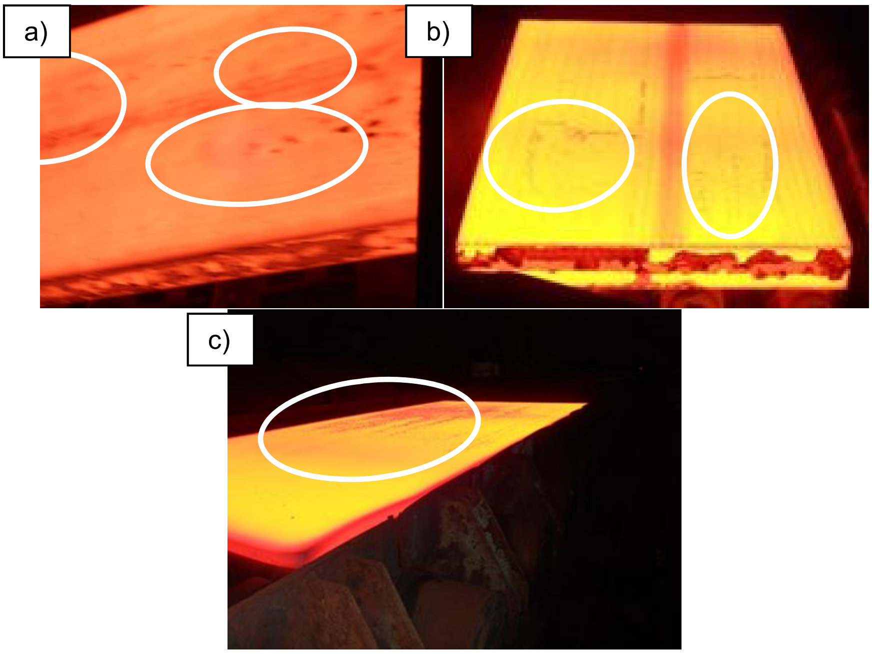

Figure 1: Examples of: **a)** and **b)** primary reheat furnace scale after primary descaling (various levels of scale depth remaining are identified by various shades of darkness) and **c)** secondary scale re-nucleation after the roughing passes of the plate showed in **a)**, the area of re-nucleation is in the same area as seen in the slab.

Examples of final plate product with primary rolled in scale can be seen in Figure 2.

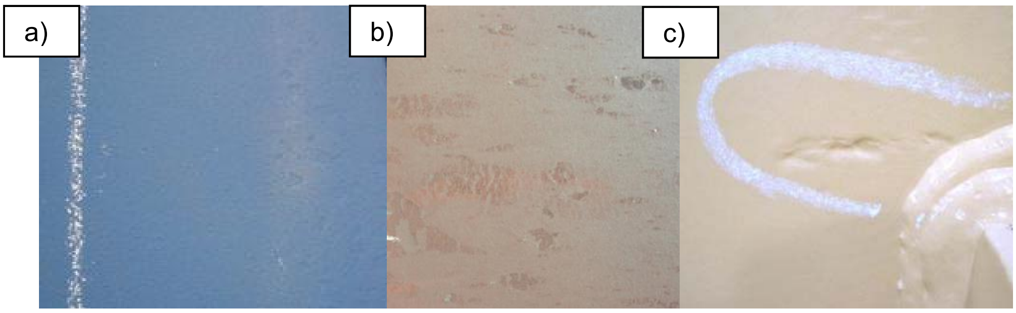

Figure 2: a) Example of rolled in secondary scale**, b) and c):** Examples of primary rolled in scale.

Measures to control reheat furnace primary scale formation are as follows:

- Reduce oxygen in the furnace to around 1%: this should reduce the thickness of the scale. This means that properly operating oxygen sensors properly located are needed (a combustion engineer will have to evaluate each furnace configuration to confirm optimum location).
- Increase the reheat furnace pressure: a positive pressure is required to avoid cold air/oxygen infiltration, in general a slight flame should be seen exiting as the furnace exit and entry doors open. Care must be taken not to have too much pressure to cause equipment damage.
- In furnaces where primary reheat primary scale is challenging, the recommendation is to keep the slab/billet temperature below 1200 °C. For almost all structural steel alloy designs, the alloys will be in solution at temperatures below 1200 °C and there is no need for higher temperatures as this only creates scale and metallurgical mechanical property stability issues. Overheating the

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surface of the slab in earlier zones should be avoided as it only creates primary scale harder to be removed.

- Time in the furnace should be limited to only what is required to achieve a uniform surface to center temperature. This depends on the slab/billet thickness; typical re-heat times are between 2.5-5.5 hours. Thermocouple trials should be used to assure that the heating profile is correct and the time required is validated. It is important to bear that time and temperature are critical to achieve good micro-alloying solubility and to minimize austenite grain growth. Variable austenite grains when hot rolled not only lead to inconsistent deformation through the thickness, but shape issues.(2)
- Furnace delays should be properly monitored and the furnace cut back to a significant level depending on the length of the delay. Excessive furnace times at high temperature result in very thick, difficult-to-remove scale at both the roughing mill and the first finishing mill stand.

Removal of reheat furnace primary scale is accomplished with high pressure water descaling systems. Primary descalers are used upon exiting the furnace and then again on the entry and/or exit of the roughing and/or finish mill stands, typically the pressure used in primary descaling after reheating and that on the mill stands are the same, ranging from 150 to 250 bars. Unfortunately, even with all of this pressure, re-heat furnace primary scale is still difficult to be removed. Because of this, many believe that the solution is to use the roughing and finish mills entry/exit descalers in all the passes, however, usually no significant improvement can be seen in the overall surface quality.

It is also important to optimize the mill primary descale passes to control secondary scale formation on remaining reheat furnace primary scale or the formation of new secondary scale. It is critical to not “over” descale as it creates other issues during the rolling process such as torque and force spikes, camber issues, head/tail end cracks, etc.

Improved removal of reheat furnace primary scale can be especially achieved at lower water pressures, by slowing the speed down through the system. Speeds between 1 m/s and 0.5 m/s or less have been found effective, however, it is important that the pumping system can sustain the pressure down the entire length of the slab with this slower speeds, essentially when considering longer time of running the system. If the pressure drops down the length of the slab, the probability that the the first ½ of the slab will look good and the second half will not is high. The pressure drop should be controlled to < 5 bars during the entire process. Excessive water pressure is usually not a problem, benefits can be obtained if the primary descale overall pressure after the reheat furnace can be increased as high as 250 bars; a pressure of 180 bars is reasonable for mills combusting low sulfur clean natural gas fuel in their reheat furnaces.

A high pressure-low volume (approximately 1/3 the water volume as the primary descale system) descale system just before the first finishing stand is highly effective for scale control. This system, due to the low water volume, can be used on all finish mill passes, except to the last pass, to effectively control the scale formation during rolling. The descaling is only done as the plate exits the mill pass due to the angle of the nozzle (directed toward the roll bite at about 15°). An example of surface quality utilizing primary mill descale vs. mill primary descale plus high pressure/low volume descale in finish mill can be seen in Figure 3.

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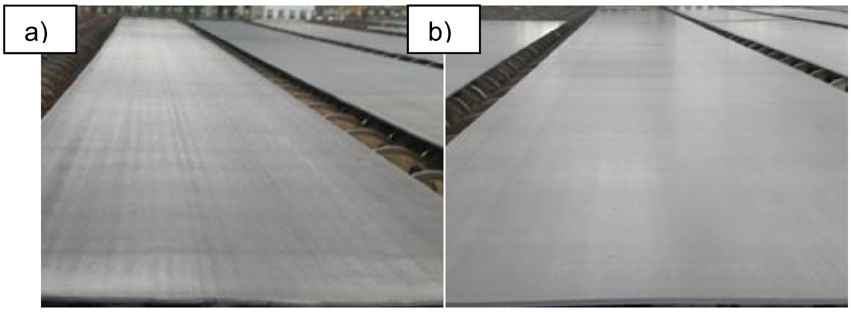

Figure 3: a) Medium thickness/carbon ship plate processed with three descaling steps (two in the roughing passes #1 and #2 and one in the finish mill pass #1), **b)** Medium thickness/carbon ship plate processed with three descaling steps, three in the primary descale (two roughing passes #1 and #2 and one in the finish mill pass #1) and high pressure/low volume descale used in the three additional finish passes (not used on last finish pass).

Additional measures can be taken to improve surface quality related to primary and secondary scale. One of them is the use of lower carbon alloy designs (≤ 0.12%) as those grades presenthave a much better surface quality as it relates to scale than those with carbon > 0.12%. Of course there are some grades where this is not possible, but there are many structural grades that could be cost-effectively produced with carbon contents ≤0.12%. Secondly, as one moves to ≤ 0.12% grades, the peritectic grades are minimized or totally avoided which significantly improves both surface and internal quality.
Another possibility is light post rolling cooling water (5-10 °C/s, depending on thickness) vs. air cooling from finish rolling temperature to 600-700 °C prior to air cooling on the cooling bed to slow/stop scale growth.

2.2 Steckel Mill Scale

Steckel mill operations not only have the traditional primary and secondary scale issues just discussed above, but also have the following points of attention:(3)

- Secondary scale formation during the Steckel rolling process;
- Plate/coil bottom head and tail rolled in scale pits due to physical contact with the Steckel drums in the heated coiling furnaces.

Secondary scale formation in the Steckel mill rolling process is also a result of the use of coiling furnaces and of the overall time spent at high temperatures per pass, the last pass rolling in a Steckel mill can be as long as 175 minutes, almost three minutes.
This issue has already been addressed in the previous sections and the suggested solutions can also be applied in the Steckel mill rolling process. As already mentioned, it can be controlled by installation of the high pressure/low volume secondary descaling system; which is used on every Steckel pass, except for the last pass.
Rolled in scale pits, on the other hand, are characteristic of Steckel mills as the rolling process requires the bottom surface of the plate or strip to come in contact with the hot coiling drums for numerous finish passes. The scale sticks to the drum and then, upon contact with the plate, this deposited scale is then re-deposited onto the bottom surface of the plate or strip, creating a “Steckel Pit”. In addition, a “jaw line” of defects is created where the plate physically goes inside of the Steckel drum, coming in contact with “teeth” like devices to allow for the plate to wrap around the drum during the rolling process.
Examples of the Steckel drum surface scale can be seen in Figure 4.

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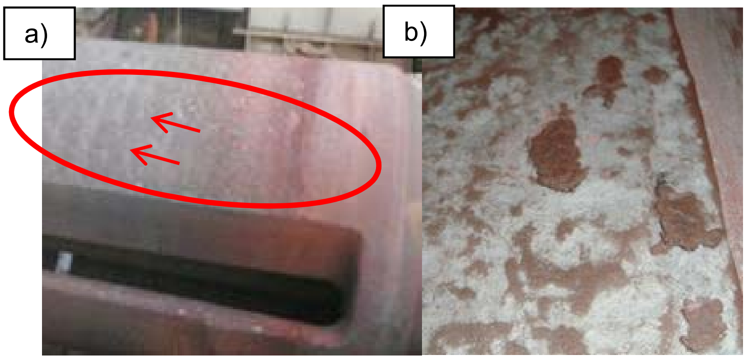

Figure 4: a) Steckel drum showing substantial scale adhering to the surface (red circle area), **b)** Detail showing scale adhering to the Steckel drum surface that gets rolled back in with contact with the plate/strips surface;

The amount of finished length affected in a Steckel mill rolled coil is directly related to the final thickness, the thickness at the start of hot coiling and the circumference of the hot coiling drum.
Figure 5 a) and b) illustrates the effects of Steckel drum diameter and of the first Steckel pass entry thickness in the overall affected length at each end of plate/strip due to rolled in Steckel pits.
The pits created can have a high frequency and have depths ranging from 0.5 – 1.5 mm, the deepest pits will be within the first length equal to the circumference of the hot coiling drum.
A characteristic shape that helps to identify these areas is a “J” shaped pit, these surfaces generally are not acceptable for surface critical applications such as painted, blasted and epoxy coated type of finishes. Such surface defects can contribute to unacceptable yield losses that are typically around 80% (slab to finish plate/coil yield) by the steel plant. Examples of Steckel rolling scale related defects can be seen in Figure 6.

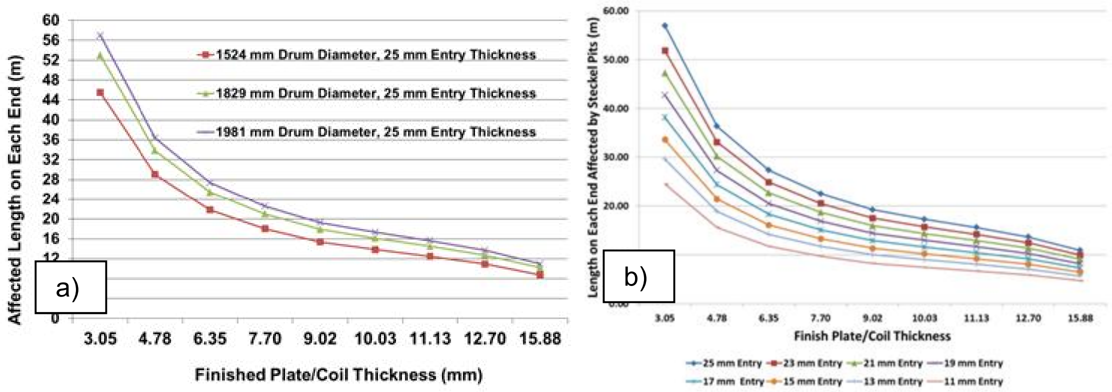

Figure 5: Example of the influence of **a)** drum diameter (constant at 1981 mm) and of **b)** first pass entry thickness (constant at 25 mm) on the total affected length at each end of plate/strip due to rolled in Steckel pits

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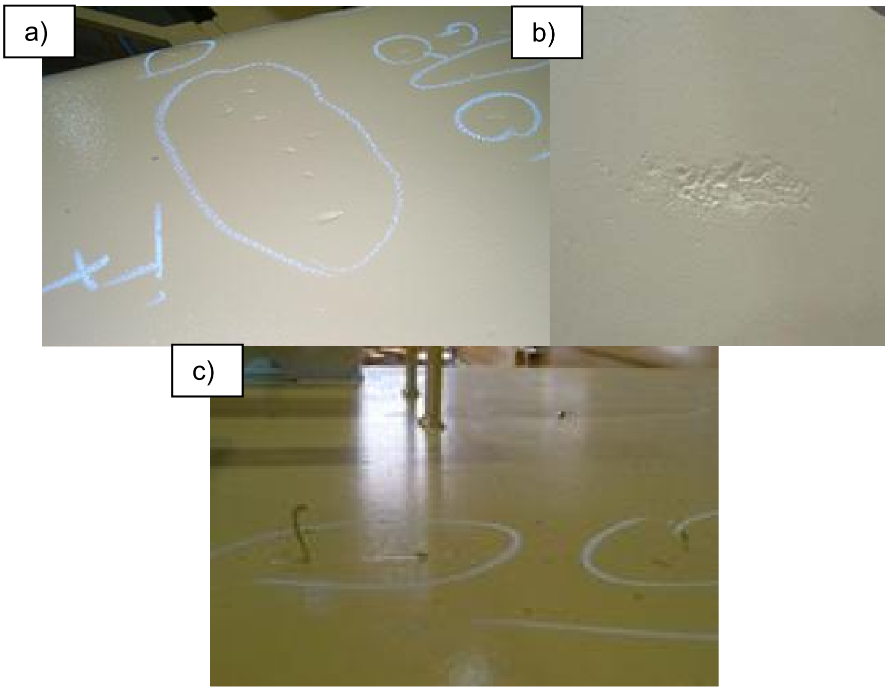

Figure 6: a) After shot blasting and painting, large white circle are pits created from the jaw line, note also pits in the other circles beyond the jaw line, **b)** Shot blasted and painted plate where the rolled in Steckel scale was not completely removed (black arrow) during shot blasting and **c)** Shot blasted and painted plate showing Steckel pits. The "J" shaped rolled in scale pit.

The two most effective methods to minimize head/tail rolled in Steckel pits are the combination of drum surface patterns, such as the one shown in Figure7 a) and b), to minimize plate/strip contact surface area and reduced tension between the Steckel drum and the mill during Steckel rolling
These two methods do not completely eliminate the problem, but they can reduce the length affected resulting in 5-10% improvement in slab to plate/strip yields.

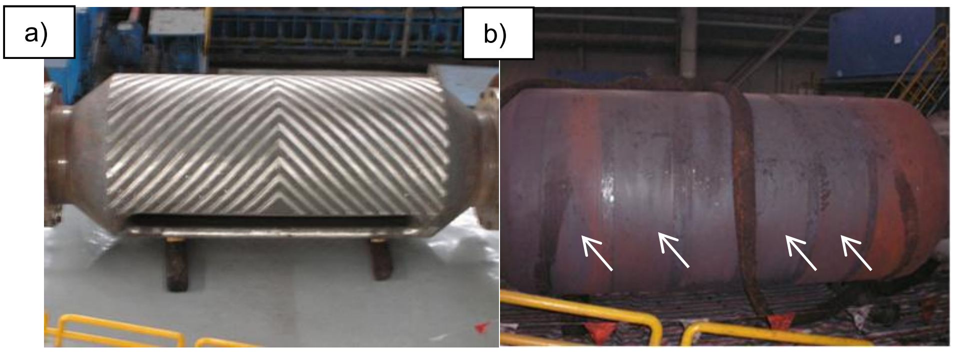

Figure 7: Example of different Steckel drum surface patterns to reduce Steckel pit surface quality: **a)** "herringbone" pattern and **b)** 5 – 100 mm wide flat raised areas.

2.3 Rolled in Foreign Debris

Rolled in foreign debris can come from several different sources. The most common sources of rolled in foreign debris are as follows:

- Slab cutting kerf, sometimes referred to as rolled in "ribbons";
- Plate/coil scraping on the side guides or mill equipment due to camber or width issues. Small pieces of steel scrap from the slab/plate/coil are scrapped off and end up on the surface and are rolled in.

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- Loose debris/scrap/tools/fasteners, etc., left near the mill from a maintenance downtime that finds their way onto the rolled surface.

Figure 8[4] show some examples of rolled in foreign debris.

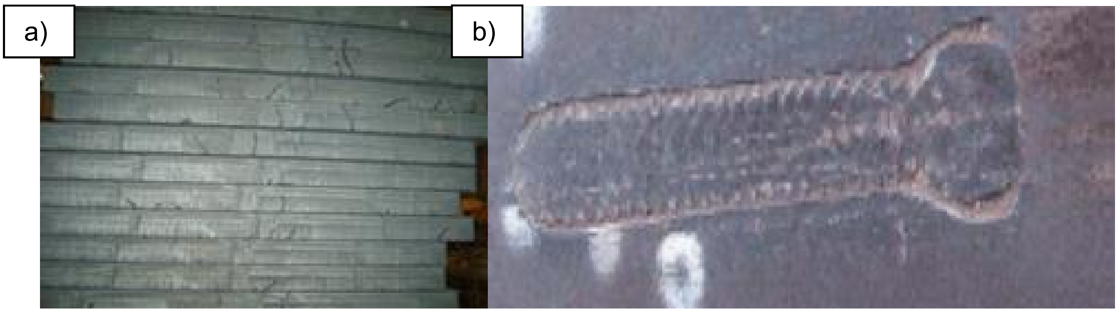

Figure 8: a) Example of slab cutting kerf that if not removed prior to rolling will result in rolled in foreign debris and **b)** Example of a bolt left near the mill that found its way onto the plate/strip surface and was rolled in**.**

Methods to minimize rolled in foreign debris are summarized in Table 2.

2.4 Rolled in Refractory

For Steckel mill operations, occasionally some refractory, from the reheat furnace or from mills with Steckel hot coiling furnaces, finds its way onto the rolled surface. Typically this type of surface defect has a white color surrounded with a reddish color, as shown in Figure 9.

Signs of rolled in refractory usually means that a furnace is in need of maintenance. Unfortunately, steel plants tend to operate furnaces beyond the expected life of some of the refractories used and do not shut down for maintenance until the rolled in refractory issues becomes commercially unacceptable. Proper furnace maintenance schedules are the only solution for this issue. Descale techniques usually are not very effective.

Table 2: Summary of methods most commonly used to minimize rolled in foreign debris

Defect origin	Actions
Slab cutting kerf/ribbons	- Assure proper casting cutting torch operation - Remove prior to reheating by gas scarfing or removal by hammer/steel bars.
Plate/coil scraping - side guides or mill equipment due to camber or width issues	- Use of proper Level 2 rolling model presizing and broadsiding functions if available - Proper use of vertical edging - Slab selection width to plate width, keep broadside ratio < 35% if possible - Assure correct set of entry/exit mill side guides - Camber control through: temperature control, tapered tail rolling in finishing, reduced head/tail force spikes, optimization of Level 2/Level 1 head to body transition control, decreased interpass reversal times to < 5 seconds for reversing mills, proper use of roll bending, assurance of mill alignment and that mill liners/chock clearances are correct, proper crown control methods in work roll profile and non-uniform finish mill work roll cooling.
Scrap/tools/fasteners, etc. left near the mill from a maintenance downtime	- To clean once per week the high pressure water mill stands to remove loose/foreign debris. -Assure that all tools, fasteners, etc. remaining from maintenance are removed from the mill stand areas. - Good housekeeping practices.

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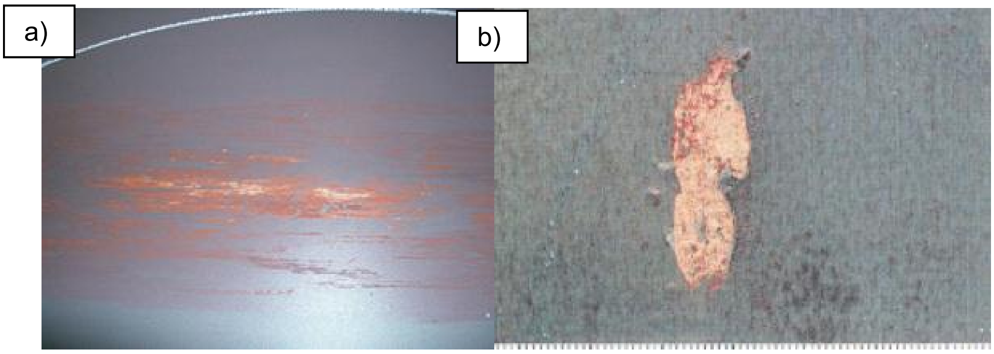

Figure 9 a) and **b)** Examples of rolled in refractory

3 BRIEF DISCUSSION ON OTHER HOT ROLLING INDUCED SURFACE QUALITY DEFECTS

Surface scale formation from other sources predominately is a result of too high of a finish temperature followed by air cooling, loose wraps in coil and improper crown in coil. Adjusting rolling finish temperature, using light post rolling cooling water use, increasing coiler tension and targeting a slight positive crown should be developed during rolling.

Mechanical handling scratches/gouges can occur during both hot rolling and cold handling of plate/coil. Common sources of hot/cold mechanically handling are reheat furnace slab entry/extraction devices, pusher reheat furnaces, frozen roll table rolls, raised roll table aprons, slab/plate bouncing on the roll table line due to head/tail turn down shape, frozen cooling bed discs, drag/push type cooling beds, plate stacking methods and broken bands on coil causing the coil wraps to unwind against each other. Many of these can be resolved with proper maintenance, modified equipment handling devices and increasing the number of bands on coils.

Edge defects created during rolling due to over use of broadsiding and/or edging can be anything from actual surface cracks to surface roll over laps, scabs, slivers, etc. In the case of over edging this is the result of either using too heavy of a draft or too many edging passes or a combination of both. In the case of over use of broadsiding when the slab width is not sufficient to adequately make the final plate width, edge cracks to appear that can be transverse or longitudinal or random mixture on either the top or bottom or both surfaces. Typically this is when broadside ratios are > 35%. Proper and limited use of edging can minimize these issues. Edging should not be used on continuous cast slabs when Level 2/Level 1 automation systems utilize presizing/broadsiding logic. Proper slab thickness and width dimensions should be used to minimize over broadsiding and improper metallurgical reduction ratios.[5]

During the course of rolling, depending on thickness, temperature, material grade (high temperature strength/flow stress), percent pass reduction, work roll diameters and work roll speed variances the head can exit the roll bite with either a turn up or a turn down located within the 500 mm of the end of the plate/slab. Beyond this point many mills also have a challenge with a “buckle/kink” that occurs approximately one meter from the end of the plate. Both situations are formed in both roughing and finish pass rolling. These raised surfaces can become overcooled during descaling passes as the water impinges on them. If the overcooling is too severe as the plate/slab re-enters the mill it is flattened during rolling potentially resulting in surface cracks to appear. Non-uniform heating in the slab reheat furnace and overcooling at the descaler will further increase the possibility of excessive turn up. Understanding

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the relationship of temperature, thickness, grade and per pass reductions on head turn up/turn down along with proper use of work roll speed differential (ski) control and optimization of head to body Level 2/Level 1 automation set up and transition are key parameters to addressing this issue.
Alloy design may influence the final surface scale quality. Lower carbon improves scale performance, lower silicon make the scale "flaky" and difficult to control and solute alloy additions of copper, nickel, chromium and molybdenum can make the scale more difficult to remove, especially nickel. Additions of copper should always be made with a nickel addition, due to copper hot shortness. The proper Cu:Ni ratio to avoid any hot shortness issues is 2:1. Proper alloy design to meet the required mechanical properties and metallurgy should also take into consideration potential surface scale quality issues.
Surface defects from overheating/burning of the slab surface during reheating are less common today than in years past. One reason for this is that today's metallurgical requirements now require overall lower slab/billet temperatures. However, it can still occur if care is not taken. Overheating/burning of the slab surface typically is a result of direct flame impingement from the furnace burners. This burner flame impingement can come from improperly adjusted burner settings, cracked burner orifice plates and excessive buildup of scale in the reheat furnace basement causing bottom burner flames to be re-directed up toward the slab surface. If overheating/burning is the cause of surface defect, during metallographic examination "ferrite fingers" may be seen.

4 CONCLUSIONS

Final plate and coil final surface quality comes from a contribution from steelmaking/casting, hot rolling and handling. A brief introduction into slab related final plate/coil surface quality issues were given along with examples. In addition, a brief introduction into metallographic characteristics and identification of root cause was shown. A majority of hot rolling induced surface quality defects were identified. For the rolling process, surface scale is far and above the most common surface quality issue that today's rolling mills struggle with. A heavy focus was made to discuss surface scale with examples of scale formation, explanations and methods to minimize its overall effect given. In addition, examples and mitigation methods were given for the other rolling induced surface quality issue. It is difficult to cover every possibility and explain details of mitigation methods in a conference paper and the authors would encourage each individual to use the information given as a beginning guideline to address their particular surface quality issues.

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