Descaling of Medium-C and High-Si, Mn Steels

Descaling of slabs exiting reheat furnaces prior to hot rolling is an important step to improve surface quality in the steelmaking process. An induction heating system with a controlled atmosphere that replicates the combustion atmosphere in a commercial slab reheat furnace was used to oxidize high-Si, Mn and medium-C steels. High-pressure water jet descaling was performed following scale formation using a laboratory setup that mimicked the industrial descaling process. Effects of nozzle impact factor (N/mm\(^2\)) on scale removability for the different steels were investigated. The critical values of impact factor required for scale removal are discussed.

Reheating of an as-cast slab to its deformation temperature prior to hot rolling is a common step in steel processing to facilitate thickness reduction and shaping to form a hot-rolled product. During reheating, cast slabs are exposed to a combustion atmosphere containing oxidizing components such as residual oxygen, \(\text{CO}_2\) and water vapor, leading to the formation of unwanted oxide scale up to several millimeters thick, which affects surface quality of the hot-rolled strip. The scale that forms needs to be removed prior to hot rolling deformation due to the adverse effect it has on the hot-rolled surface quality, the roll-strip interfacial behavior and other undesired effects. Scale removal is normally achieved by high-pressure (up to about 4,000 psi) hydraulic water jet descaling. The efficiency of descaling is strongly influenced by the complex structure of the formed oxide scale, as well as descaling process parameters including nozzle design, hydraulic parameters and process mechanical design. The characteristics of the formed oxide scale are highly influenced by steel chemistry, temperature and furnace atmosphere conditions. Because these multiple factors can interact with each other, comprehensive analysis of the descaling process in industrial practice is urgently needed. Steel chemistry and minor
Hydraulic parameters for descaling are often characterized numerically using a so-called impact factor (IF), which is described as the ratio of the total impact force (IT) from a spray nozzle to its total coverage area (IT/A). Hydraulic parameters such as nozzle height, which affects the impact factor, have been shown to have a strong effect on descaling efficiency. However, there are few studies published that analyze the effect of alloying elements in steels on scale removability, and also only limited information on the critical value of impact factor needed to remove scale efficiently.

Inefficiencies during descaling have adverse effects on the hot rolling process, with the formation of defects resulting from unremoved residual scale during descaling, which affects the final surface quality of the rolled product. A critical look into how specific elements such as C, Mn and Si in steels affect descaling efficiency and how hydraulic parameters can be manipulated to improve scale removability is of much interest to the steel industry.

In this article, a set of experimental laboratory cast steels that included a base medium-C steel and several steels alloyed by Si and Mn were examined. The combustion gas atmosphere in industrial reheating furnace was simulated in laboratory reheating tests and a special descaling device based on a CNC-controlled mechanism was used to control slab and nozzle displacement to perform hot descaling tests.

### Experimental Procedures

The composition of the steels used in this study are presented in Table 1. This set of laboratory cast steels included: a base composition with low levels of C, Mn and Si, a medium C, a high Mn, and a high Si composition. The cast plates where carefully machined to 165 mm x 110 mm x 20 mm to remove the cast surface for this study. Machined samples were finished using wet grinding with 60 grit silicon carbide and the surface quality of the ground sample was measured to have Ra of 0.271 µm using 3D optical profiler (Nanovea, Model PS50 Micro Photonic Inc.). To prevent rusting prior to testing, sample surfaces were preserved by cleaning with ethanol and air drying.

To simulate industrial scale formation during reheating, the samples where reheated in a 35 kw LSZ induction melting furnace (Model LSZ-35), having a 200 mm x 130 mm x 25 mm induction chamber which was embedded in an enclosure to allow for control of the furnace atmosphere (Fig. 1). The top of the furnace chamber was covered with kaowool during reheating. The furnace was equipped with a multi-channel gas mixing system and the gas was delivered to the chamber using a ceramic tube. The atmosphere of the industrial reheating furnace was simulated by mixing gases in proportions that reproduced the natural gas combustion atmosphere in an industrial furnace (Table 2). The composition of gas mixture was controlled using a multi-channel mass flow control system and a controlled temperature water saturation system. An excess oxygen level of 2% was chosen for this study based on observed industrial reheat furnace operating conditions. The gas flow rate supplied to the heating chamber was 6,000 ml/minute, which provided a 2 cm/second gas velocity in reaction zone. Calculations confirmed the absence of gas starvation in the reaction zone at this flow rate. The temperature during reheating was controlled by a K-type thermocouple inserted into the slab. The thermocouple enabled adjustment of the furnace power to control the reheating temperature within ±10°C. The reheating temperature and time employed for the test was 1,200°C for 90 minutes, which is typical for soak zone temperatures and residence times of industrial reheat furnaces.

At the end of the oxidation period, the sample was carefully removed from the furnace chamber and quickly transported into a descaling chamber to avoid cooling prior to descaling. The hot sample was subjected to hydraulic descaling using high-pressure water. A CNC stage setup was used for descaling (Fig. 2) that allowed the standoff distance from the sample surface to the nozzle to vary during

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Lab Cast Steels Used in This Work (wt.%)</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>----</td>
</tr>
<tr>
<td>Base</td>
</tr>
<tr>
<td>Medium C</td>
</tr>
<tr>
<td>High Mn</td>
</tr>
<tr>
<td>High Si</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial Reheating Conditions Simulated in Laboratory Oxidation</td>
</tr>
<tr>
<td>Combustion gas, vol.%</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>8.5 CO₂, 17 H₂O, 2 O₂, N₂ bal.</td>
</tr>
</tbody>
</table>
Induction furnace reheating in control atmosphere setup.

Descaling setup using a CNC stage.
the descaling process. This approach allowed descaling to be conducted at different spray heights that corresponded to different IFs (N/mm²). The descaling was conducted at a spray and lead angle of 15° at a flowrate of 4 l/minute at 4,000 psi and a speed of 0.01 m/second. The standoff distance (Z distance of the CNC) was programmed to vary across the length of the sample by decreasing the height of the spray nozzle to cause a corresponding increase in IF. The experimental IF related to nozzle position was verified using pressure gauges in a sponsor facility (Spraying Systems Co.) and designated in this article as “low IF” for 1 N/mm², “medium IF” for 1.4 N/mm², and “high IF” for 2.2 N/mm². After descaling, the plate was quenched with cold water to prevent the development of secondary scale. The three footprints formed during descaling with varying IF were coated with epoxy to preserve the surface for subsequent examination.

A water jet was used to extract rectangular 10 mm x 15 mm x 20 mm samples from different footprint zones along the length of the sample. A sample with the original formed scale was also extracted from the non-descaled part of the sample for analysis. All extracted samples were cross-sectioned, mounted in epoxy, ground using silicon carbide abrasive papers to 1200 grit and mechanically polished with 0.1 µm diamond paste using low polishing pressure to minimize scale breakage. The morphology, thickness, microstructure, and chemistry of the original and residual oxide layers were analyzed with a scanning electron microscope (SEM) using an TESCAN-ASCAT system equipped with Bruker energy-dispersive spectroscopy (EDX). A quantitative approach was used to evaluate the descaling efficiency by classifying the descaled surface into three structures and measuring the percentage of each structure on cross-sectional samples extracted from the descaled surface. The quantification was done for the entire width of the extracted descaled area (15 mm) by taking SEM images of 20 or more frames at different magnifications between 20 and 100 µm. ImageJ software was used as a measuring tool to quantify the three different surface classes.

Results

Scale Formed During Reheating

Base Steel: The top row of Fig. 3 shows the cross-sectional microstructure of the scale that formed on the base steel having low levels of C, Mn and Si oxidized at 1,200°C for 90 minutes in a combustion gas atmosphere. The scale structure consisted of an external layer (outer and intermediate) growing outward and internal layer (inner merged with subsurface) growing inward. The external scale thickness measured between 850 and 1,000 µm and the internal scale measured between 45 and 90 µm. The external scale layer was characterized by a continuous dense structure while the internal scale layer saw high levels of porosity between the scale/steel boundary with metal-oxide entanglement. The scale structure in the internal layer was non-uniform and discontinuous in different sections and also showed adhesion to the substrate in some section while other sections showed complete separation from the substrate. EDX chemistry analysis of the oxide scale revealed the external scale layer to contain Fe-based oxide and phase identification with Raman spectroscopy revealed the presence of Fe₂O₃ and Fe₃O₄ phases in this layer. The internal layer contained a mixed chemistry of pure Fe with trace Cu, Fe-based oxides and Fe-Si based oxides. Phase identification revealed this layer to be a mixed phase of Fe₂SiO₄ and Fe₃O₄. A randomly scattered layer containing pockets of oxides also formed internally and was superimposed on the metal substrate and extended about 30 µm deep into the substrate from the scale/steel boundary. The chemistry of that layer showed the presence of a mixed Fe-Si-Mn-based oxides.

Medium-C Steel — Cross-sectional microstructure of the medium-carbon steel (Fig. 3, second row) revealed a significantly different structure than that formed on the base steel. The external scale layer measured between 600 and 700 µm and the internal scale measured between 25 and 70 µm. The external layer was a dense scale structure, having transverse cracks running through it. The external layer was partially separated from the internal scale layer. The bottom part of the internal scale layer exhibited significant root-like penetration into the metal substrate. Some penetration of the metal substrate by a root-like subsurface layer was as deep as 100 µm and appeared to have strong adhesion to the metal substrate. Fe metal was also seen in the internal layer and was randomly distributed across the inner and subsurface layers. Chemistry analysis on the different scale layers revealed similar Fe-based oxides and Fe-Si based oxides in the external and internal scale layers, respectively. Raman spectroscopy revealed the external layer to be mostly Fe₂O₃ and Fe₃O₄ phases and the internal layer to be a mixture of Fe₂SiO₄ and Fe₃O₄ phases. This suggested that carbon in steel changed scale morphology (structure and thickness) but did not have an effect on the scale layer chemistry and phases present.

High-Si Steel: In the case of the high-Si steel (Fig. 3 third row), the scale structure was characterized by randomly distributed voids in the external outer layer through to the internal subsurface scale layer. The external scale layer measured between 1,000 and
Cross-sectional backscattered electron (BSE) image and chemistry of scale structures present in steels reheated at 1,200°C before descaling.

<table>
<thead>
<tr>
<th>Steel</th>
<th>External layer (outer &amp; intermediate)</th>
<th>Internal layer (inner &amp; subsurface)</th>
<th>Chemistry wt. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td>Fe: 83, O: 17, Si: 99, Cu: 2, Mn: 63,</td>
</tr>
<tr>
<td>Medium, C</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td>Fe: 83, O: 18, Si: 98, Cu: 3, Mn: 64,</td>
</tr>
<tr>
<td>High, Si</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td>Fe: 81, O: 18, Si: 100, Cu: 3, Mn: 61,</td>
</tr>
<tr>
<td>High, Mn</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td>Fe: 81, O: 17, Si: 81, Cu: 4, Mn: 58,</td>
</tr>
</tbody>
</table>
1,200 µm in thickness and the internal scale thickness measured between 80 and 190 µm. The internal layer structure merged with the inner and subsurface oxide structure, with a significant amount of metal entrainment. The internal scale layer was well bonded to the metal substrate and was disconnected from the external layer in some sections, with non-uniformity in that layer. Elemental mapping showed the internal layer to be a Si-based oxide layer with some Fe-based oxides in it. The internal scale layer was connected to the substrate at the scale/steel boundary. This structure could have resulted from the formation of a low melting temperature (1,180°C) fayalite eutectic. Phase identification supported the presence of this phase, which can melt during reheating at 1,200°C, within a mixture of Fe₂SiO₄ and Fe₃O₄ phases in the inner scale layer.

High-Mn Steels: The high-Mn steel was characterized (Fig. 3, bottom row) by uneven thickness in the external scale layer, which measured between 900 and 1,100 µm. Transverse cracks running from the external layer through to the internal scale layer as well as voids at the external/internal oxide layer boundary were observed. The internal scale layer, which measured between 50 and 80 µm, was characterized by a multi-phase oxide mixture that penetrated into the metal substrate. Metal entrainment in this layer was massive with metal particle sizes of up to 50 µm. Internally formed oxide pockets below this layer on the substrate was extensive for the high-Mn steel. The internal scale layer had a coherent structure at the scale/steel boundary. Chemistry analysis of the external scale layer was observed to be pure Fe oxide with trace amounts of Mn. The internal layer consisted of a mixed chemistry with the presence of Mn increasing in concentration from the external to the internal interface. Phase analysis of the internal layer (inner and subsurface) identified the presence of Fe₂SiO₄ and Fe₃O₄ phases, while Mn-bearing oxides were detected in pockets formed in the subsurface layers. Phases were not identified in these small pockets; however, thermodynamic simulations predicted the formation of MnSiO₃ and Mn₂SiO₄ phases in this subsurface region.

Classification of Descaled Surface Quality — Reheated steels were subjected to water jet descaling with variations in the IF. To obtain quantitative data from these experiments, the quality of the descaled surfaces was grouped into three surfaces classes (Fig. 4):

- **Class A** had a completely removed external, complex internal and subsurface oxide.
- **Class B** had a completely removed external layer and partially removed internal (inner and subsurface) scale layer, particularly, with presence of the Fe₂SiO₄ phase.
- **Class C** had complete removal of the external and internal (inner scale) layers but contained penetrating subsurface oxide with root-like scale structure having metal entrainment.

**Descaling Efficiency**

**Base Steel:** Analysis and quantification of the surface quality of the descaled base steel composition showed significant difference in efficiency with varying IF (Fig. 5). It was observed that the low-IF condition demonstrated complete removal of the external (Fe-oxides) and partial removal of the internal (mixed Fe-Si based oxides) scale layers, making up 70% of clean surface quality class A and 30% class B plus C. The residual scale (class B and C) contained partially removed internal oxide layer (inner and subsurface). Increasing IF to the medium condition showed a

![Figure 4](image-url)
A decrease in the residual scale from 20% to 12% particularly for class B, with a corresponding increase in the clean surface (Class A). The residual scale thickness also decreased from 5–12 µm range to 3–5 µm. The residual scale, particularly for the remaining class C, consisted of consolidated oxides between entrapped metal particles in the subsurface layer. At the highest IF condition, a significant amount of the residual scale was removed and replaced by secondary iron oxide scale that formed after the descaling process. Some of the scale formed within metal crevices were removed and secondary oxides formed in its place. The clean surface quality was quantified to be 94%, with the residual scale making up the remaining 6%, which was class C-type scale structures. The thickness of the residual scale was less than 5 µm.

Medium-C Steel: This carbon steel was characterized by deep penetration of internal scale layers (inner and subsurface) into the metal matrix (Fig. 3). Descaling at the low-IF condition exhibited complete removal of the external and partial removal of both classes of internal scale layers (class B and penetrated subsurface class C) (Fig. 6). Residual scale thickness after descaling measured up to 20 µm in thickness. Quantification of the surface quality revealed that almost 50% of the residual scale (class B and C), which consisted of Fe$_3$SiO$_4$ and Fe$_3$O$_4$ oxide phases, remained on the surface at the low-IF condition. These residual oxides were well connected to the substrate due to the massive root-like oxide penetration seen in the subsurface for this steel chemistry. At the medium-IF condition, there was a significant decrease in the amount of residual scale, particularly for
Surface quality of medium-C steel after descaling at different IFs.

<table>
<thead>
<tr>
<th>IF</th>
<th>Class A</th>
<th>Class B</th>
<th>Class C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>53</td>
<td>19</td>
<td>28</td>
</tr>
<tr>
<td>Medium</td>
<td>75</td>
<td>9</td>
<td>16</td>
</tr>
<tr>
<td>High</td>
<td>85</td>
<td>3</td>
<td>12</td>
</tr>
</tbody>
</table>

Surface class B, which did not contain deep penetration and a less complex structure than that of surface class C. The thickness of the residual scale for this IF decreased to about 13 μm and accounted for 25% of the quantified surface coverage, while the clean surface Class A accounted for 75% of the coverage. It was observed that most of the oxide penetration (class C) had different orientations: vertical, horizontal and twisted geometry with different angles of penetration. The majority of the residual scale class C consisted of complex oxides. At the high-IF condition, it was observed that the complex oxides with penetration were partially removed. Oxide penetration with a vertical orientation was removed, while oxide penetration with the twisted and slanted orientations were only partially removed. At this IF condition, the residual scale consisted predominantly of surface class C (12%) with the scale thickness measuring up to about 10 μm. Near 85% of the surface was quantified as clean (class A).

**High-Si Steel:** Characterization of the original scale structure prior to descaling demonstrated a complex mechanism of internal scale formation, including possible liquid fayalite formation (Fig. 3). The internal layer was also uneven due to a significant amount of porosity and voids in the internal scale layers and had scale thickness measurements as high as 190 μm and as low as 80 μm. At the low-IF condition, only 34% of the quantified surface quality was completely removed (class A) (Fig. 7). The remaining scale was a mixture of surface class B (27%) and C (39%). The residual scale measured up to 85 μm in thickness, which was about half of the original internal scale.
layer thickness. At the medium-IF condition, there was no significant change in the percentage of clean surface class A, as was seen in the base and medium-C steel. The residual scale measured up to about 50% with a 9% decrease in class B scale residue (from 27 to 18%) and 5% decrease in class C (from 39 to 34%). The residual scale was characterized by a mixed fayalite and entrained metal layers, showing strong attachment to the substrate. At the highest IF condition, the quantified surface quality did not show any significant improvement from the previous medium IF. The total clean surface at this point was 53% and the residual scale 47% (17% class B and 30% class C). The majority of the residual scale was made up of class C, which was almost twice of the amount observed in class B. Observations of the residual scale revealed that some residual scales were strongly attached to the underside of the entrained layer of metal, making it difficult to remove since direct contact with the impinging water pressure during descaling was blocked. The residual scale measured up to about 60 µm in thickness, which was a 15 µm decrease from the first IF condition of 1.0 N/mm². Overall, the high-Si steel showed significant resistance to descaling, as evident from its high levels of quantified residual scale percentages and this can be attributed to the complexity of the formed oxide in the internal scale layers of this steel.

**High-Mn Steel:** Similar to the high-Si steels, the high-Mn steel showed a lower descaling efficiency (Fig. 8). The original scale structure of the high-Mn steel was characterized by large amount of metal entrapment and penetration of the subsurface internal oxide layer.

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**Figure 7**

Surface quality of high-Si steel after descaling at different IFs.
into the matrix (Fig. 3). The residual scale measured at low IF decreased from 70% to 40% at the highest IF. There was a gradual improvement in the residual class A quantified surface percentage as it increased from 30% to 60% at the highest IF. The residual scale (class B and C) was characterized by oxide penetration into the metal matrix as well as an adherent Fe$_2$SiO$_4$ oxide phase, which exhibited a strong connection at the scale/steel boundary in the internal scale layer. The residual scale thickness measured after descaling with the low-IF condition decreased from about 40 µm to about 20 µm when the highest IF condition was applied. Surface class C was the predominant residual scale type, having penetration extending 50 µm into the substrate from the oxide/steel interfacial boundary.

### Discussion

The testing methodology based on the CNC-controlled descaling process allowed for the IF testing conditions to be changed on a single test sample and descaling test results to be obtained while minimizing possible errors associated with using multiple test samples. The effect of impact factor on descaling efficiency for the different steel grades tested is presented in Fig. 9. It was observed that a critical IF condition between medium (1.4 N/mm$^2$) and high (2.2 N/mm$^2$) was enough to descale the baseline steel sample and that the residual remaining scale coverage was about 6% for surface classes B and C, with the clean surface class A percentage measuring 94%. In the case of the medium-C steel, the critical high-IF condition was just enough to remove close to 90% of formed scale.
However, residual scale class C with metal substrate oxide penetration was the predominant residual scale type and other scale removal approaches may be needed for its removal. For the high-alloy steels (Mn and Si), it was observed that the critical IF condition required for greater than 90% efficiency was above studied 2.2 N/mm², as the residuals in these steels contained high percentages of both surface class B and C and had significant remaining oxide thickness (Fig. 10).

Comparison of the residual scale (class B and C) remaining after descaling indicated a decrease in thickness with increasing IF (Fig. 10). The high-Si steel retained the highest residual scale thickness (60 µm) after descaling for the highest studied IF condition of 2.2 N/mm², followed by the high-Mn steel (18 µm), while the medium-C and base steels were both below 10 µm in thickness. This result indicates that the major alloying elements (Mn and Si) play a strong role in decreasing descaling efficiency and this role can be attributed to the complexity of oxide scale interface structures formed on these steels when reheated in a combustion gas atmosphere.

Conclusions

Scale formation during reheating in combustion atmosphere followed by descaling was studied using four laboratory cast steel grades, including a low- and medium-C steel with low residuals and two highly alloyed Si and Mn steels. The sample descaling efficiencies were accessed using three water jet descaling impact factors (low, medium and high IF). The scale structures formed on these steels during reheating exhibited distinctly different chemistries and morphologies (thicknesses, topology and uniformity) in their internal and external layers. The methodology to quantify descaling efficiency based on percent coverage for three defined categories of residual scale structure was proposed. Descaling tests showed that the structure of internal layer and deeply penetrated oxide features into metal matrix sublayer are the
most important factors influencing scale removability. Scale formed on the medium-C steels had oxide penetration which affected its descaling efficiency. Residual scale structures observed after descaling contained root-like penetrating oxides. For the case of alloyed steels, the high-Si steel was characterized by an adherent fayalite phase with significant metal entrainment and this layer showed a high resistance to descaling. The Mn steel also contained root-like penetrating oxides and entrained metal that was strongly attached to the subsurface scale, which hindered direct contact with the impinging water pressure during descaling and hence resulted in a lower efficiency. Other factors such as internal scale thickness and defect formation in the scale structure accounted for the lower descaling efficiency in the alloyed steels. The critical IF conditions required for the efficient scale removal for the alloyed steels were determined to be above 2.2 N/mm², while between 1.4 to 2.2 N/mm² was enough to achieve efficient scale removal for the base and medium-C steels.

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References


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