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Causational Analysis and Rectification of Issues Concerning Scale Formation on Hot-Rolled Straight Bar Product and its Effects on Ultrasonic Testing

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Honors Research Project

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Abstract

An investigation at Charter Steel in Cleveland, Ohio, aimed to improve ultrasonic testing accuracy by enhancing Straight Bar Quality (SBQ) hot rolling cooling procedures. SAE steel grades 1010, 10B23, 4140, 10V40, 1080, and 8620 were analyzed. Initial observations revealed differences in scale formations and ultrasonic results among different steel grades, prompting a reassessment of scale formation mechanisms. Experimental trials showed decreased scale adherence and porosity with higher cooling rates, leading to improved surface quality. Metallurgical analysis found a bainitic surface structure in samples with higher cooling rates, while SEM analysis linked silicon content ≥0.15wt% with porous scale formation in non-boron steel alloys. Mechanical testing confirmed improved surface quality with higher cooling rates. Final UT scans demonstrated reduced noise levels for cooled material, signaling progress in mitigating interference. Ongoing trials aim to refine cooling parameters for optimal ultrasonic accuracy, promising streamlined steel grade selection, enhanced processing efficiency, and improved product quality at Charter Steel.

Executive Summary

An investigation aimed at enhancing ultrasonic testing procedures for Straight Bar Quality (SBQ) steel was conducted at the Charter Steel facility in Cleveland, Ohio. The study delved into various aspects, including scale formations, metallurgical characteristics, mechanical properties, and surface chemical compositions, to identify factors negatively influencing UT accuracy and efficiency. Initial observations revealed discrepancies in scale formations and ultrasonic test results across different steel grades, prompting a reassessment of existing hypotheses regarding scale formation mechanisms.

Experimental trials were conducted to systematically evaluate the impact of cooling rates during hot rolling on scale adherence and surface characteristics. These trials demonstrated that scale adherence and porosity decreased with an increase in cooling rate. The entrapment of air bubbles within the scale by these two characteristics were later found to be the cause of background noise within prior ultrasonic scans.

Metallurgical analysis provided valuable insights into the grain structures of cooled SBQ steel samples, highlighting the influence of cooling rates on scale formation and surface quality. Notably, a bainitic granular structure was observed within the outer surface of samples subjected to higher cooling rates.

Chemical analysis further clarified the role of silicon content in scale formation, shedding light on a silicon oxide phenomenon rarely discussed within the industry. Silicon concentrations of greater than or equal to 0.15wt% were found to correlate to the formation of porous scale layers and increased scale spalling on non-boron alloys. Furthermore, boron additions were found to enhance spalling significantly for low carbon steel. These insights into the effects of chemical composition of SBQ steel offer valuable guidance for future trialing of new steel grades as well as a better understanding of the maximum abilities of the rolling facility.

Mechanical testing complemented the findings by demonstrating improvements in surface quality with higher cooling rates, resulting in reduced scratching and improved visual surface quality. These mechanical properties are a fortunate result of increased cooling rates which may be required for many future steel orders.

The culmination of these findings was evident in the final ultrasonic scans, in which one batch of 8620 SBQ was cooled, and one batch was not. The cooled material exhibited a remarkable decrease in noise levels, indicating progress in mitigating background interference. Ongoing trials aim to refine cooling parameters further to achieve optimal reduction in noise levels and enhancement of ultrasonic testing accuracy.

In conclusion, the findings from this comprehensive investigation provide valuable insights into the complexities of UT for SBQ steel with regards to cooling rate and scale formation and will help to create practical solutions for enhancing testing accuracy and efficiency in the near future. Implementation of these insights promises to streamline steel grade selection, improve processing efficiency, and ultimately enhance product quality at Charter Steel.

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Introduction

Scale formations on specific grades of Straight Bar Quality (SBQ) steel can impede the Ultrasonic Testing (UT) thereof. This inability to certify materials to customer specifications represents a large opportunity cost for steel companies. If these scale formations are metallurgically related, then the specific scale formations will exhibit distinct patterns in response to different temperature conditions during hot rolling. Through systematic experimentation and procedural design, it is hypothesized that one can identify optimal temperature settings to mitigate or reduce the appearance of these problematic scales and enhance the feasibility and accuracy of UT while maintaining surface and metallurgical quality throughout the SBQ steel.

This project builds upon the understanding of silicon scale formation as discussed by F.H. Stott, where silicon oxides slowly form within the metal/metal oxide (M/MO) interface of Fe-26Cr-1Si and promote porosity and spallation of the metal oxide layer (Stott *et al.*). It is eventually found that this unique phenomenon also occurs with lower alloying content, and that controlling the steel temperature during the end stages of hot rolling can largely inhibit this process.

Background

UT is a non-destructive testing method commonly used in various industries, including the steel industry, to evaluate the integrity of materials. UT of SBQ products involves the use of high-frequency sound waves to detect internal defects within the material. UT offers several advantages for inspecting SBQ products, including its non-destructive nature, high sensitivity to internal defects, and capability to inspect large volumes of material rapidly.

The SBQ steel is first straightened by multiple rollers to ensure bar alignment within the testing equipment. This process also has the added benefit of removing scale from most industry produced SBQ product. Next, a constant jet of water is shot across each individual bar and an ultrasonic transducer is placed on the surface. This transducer emits high-frequency sound waves into the material. These waves travel through the material until they encounter an interface (such as a boundary between different materials, a solid defect, or an otherwise nonuniform structure). As the sound waves propagate through the material, they undergo reflection, refraction, and attenuation based on the material's properties and any defects present. When a sound wave encounters a defect, part of the energy is reflected to the transducer while the rest continues to propagate through the material. This reflected energy is recorded by the transducer and displayed in real time for the operator as the bar is scanned from one end to another. Therefore, a spike in recorded energy is seen by the operator as a potential internal defect.

Initial trialing and testing of UT at the Charter Steel Processing Facility would often yield data with extremely large amounts of feedback, as shown in **Figure 1A**. Any legitimate data that could be analyzed was hidden by this severe noise in the sample. Some tests, however, would yield a typical data stream with energy peaks that directly align with the location of internal defects, as shown in **Figure 1B**. The observation was quickly made by the operators that certain grades of steel would produce a “noisy” image, while others produce a “clean” image. The main grades that were determined to produce a “clean” image were low carbon grades at around 0.1% to 0.2% carbon, and boron grades, with boron being the better of the two. Meanwhile, 4140, 8620, and 1080M were all noted as being “noisy” grades, with 8620 having the worst perceivable background echoing.

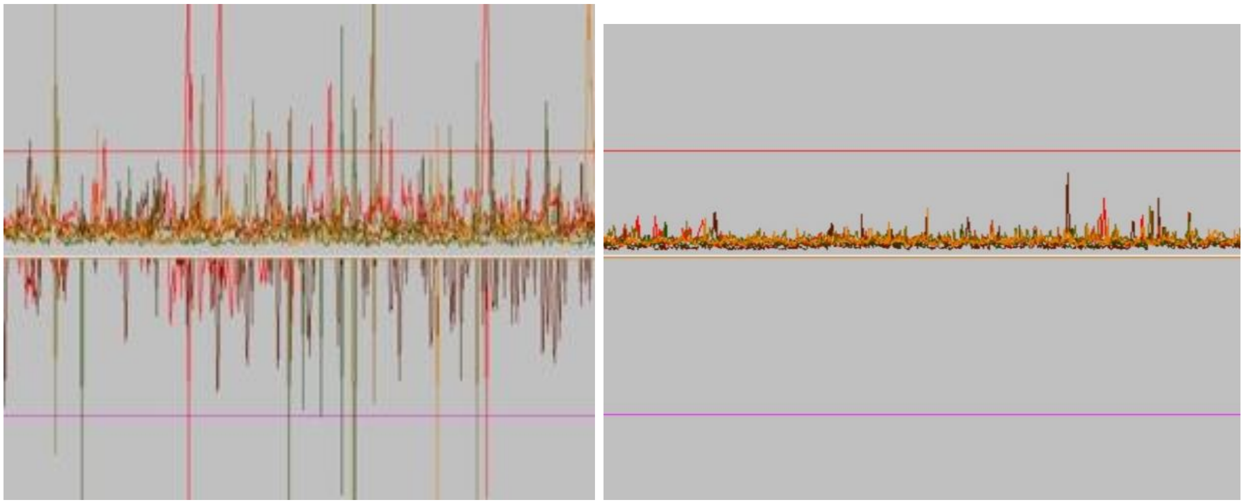


Figure 1: (A, left) Ultrasonic feed with high amounts of feedback/noise; **(B, right)** Ultrasonic feed with acceptable levels of feedback and acceptable noise.

This background noise severely impacted the qualitative abilities of the processing facility, and certain SBQ orders with UT requirements were unable to receive UT quality certifications. This inability to produce UT certified material represented a large opportunity cost to the company if left unresolved.

In addition to these issues, individuals who were contracted by Charter Steel to perform preventative maintenance on the straightening equipment expressed that the amount of mill scale collected from the straightener was remarkably low. Most other facilities would collect enough mill scale to fill a 4.5’x4.5’x4.5’ container in less than a week, while the collection hopper at the Charter Steel Processing Facility would fill roughly once every three months. This led to the acquisition of multiple bundles of 4140 SBQ steel from other sources. During the straightening process, the scale easily fell off and the UT scans were reminiscent to that of **Figure 1A**. Meanwhile, analysis of the microstructure showed the existence of martensitic formations within the core of this outsourced SBQ steel, proving a very high cooling rate was utilized during hot rolling of the product (**Figure 2**).

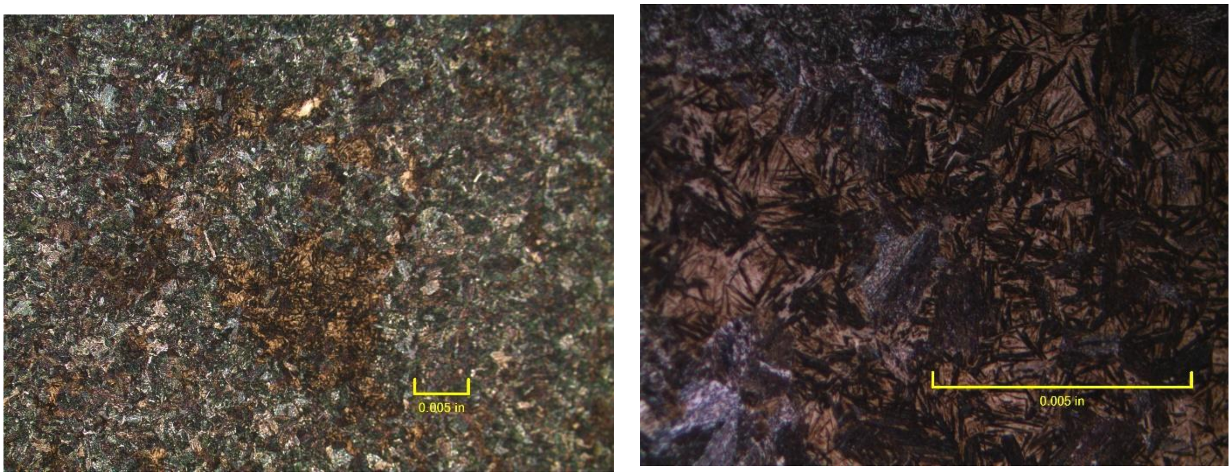


Figure 2: (A, left) Steel sample surface from alternative manufacturer, core at 100x magnification; **(B, right)** core at 500x magnification.

With further research, it was determined that echoing can occur simply due to the presence of well adhered mill scale to the surface of the bar (Zhai *et al.*). However, the severe echoing observed with problem grades of material is far more erratic and discontinuous than what would be expected from this phenomenon. It was evident that other significant factors were at play in this phenomenon.

In terms of physical observations, the scale on the surface of low carbon and boron steels was described as “thick” or “powdered” by the operators of the equipment and would crack and flake off the bar easily. The “noisy” grades of steel were instead described as having a “bubbly” or “pocked” scale surface, with an exceptionally adherent scale. This phenomenon, known as “pocking” to the operators and engineers in the plant, is a scale formation commonly seen from Charter Steel SBQ product. This formation led to the early hypothesis that the scale was flaking off from the steel with relative ease once exposed to the water jets of the UT, and the scale would float within the water film layer near the surface and cause feedback interference. All of this appeared to occur despite the straightening process, which should easily descale the bar.

An inspection of “problem” grades of 4140 and 8620 SBQ was soon conducted; There was little to no flaking on the scale surface, and pocking did not seem as prominent as the UT results would lead one to believe (such as the example in **Figure 3A**). The scaling seemed akin to a powder coating, as rubbing the surface would leave a dark powder on the glove or rag (**Figure 3B**). Meanwhile, low carbon and boron grades had obvious chips and cracks in the scale layer.

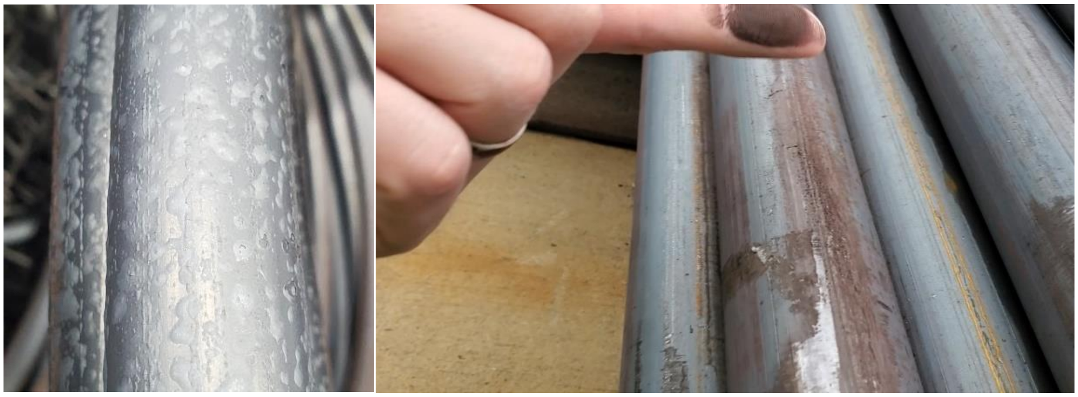


Figure 3: (A, left) Severe pocking on the surface of low carbon steel; **(B, right)** 4140 grade SBQ with a “powdery” surface scale.

Observations of the chemistry of the various grades (shown in **Table 1**) shows that both 1080M and 8620 had a 0.1wt% compositional requirement for nickel, a substance commonly known to promote scale adhesion based upon operator experience. However, 4140 shared an overlapping nickel content range with both low carbon grades and boron grades; nickel alone could not be the cause of scale formation which creates consistent and immense background noise since certain grades within its range never had such issues. On the other hand, 4140 does contain a significant amount of chromium.

Table 1: Nominal compositions of the six main steel grades tested during trials.

GRADE	Composition (wt%)																	
	C		Mn		P		S		Si		Ni		Cr		Mo		B	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
10V40	0.4	0.45	0.7	0.8	0	0.05	0	0.05	0.15	0.25	0	0.2	0	0.2	0	0.05	0	0.0005
10B23	0.2	0.25	0.7	1.0	0	0.02	0	0.02	0.15	0.3	0	0.1	0	0.1	0	0.05	0.001	0.003
1010	0.08	0.12	0.25	0.4	0	0.02	0	0.02	0	0.1	0	0.1	0	0.1	0	0.05	0	0.0005
1080M	0.75	0.85	0.7	0.8	0	0.02	0	0.02	0.2	0.3	0.1	0.2	0.1	0.2	0	0.05	0	0.0005
8620	0.15	0.25	0.7	0.9	0	0.02	0	0.02	0.15	0.3	0.4	0.6	0.4	0.5	0.15	0.3	0	0.0005
4140	0.35	0.45	0.75	1.0	0	0.02	0	0.02	0.15	0.35	0	0.2	0.95	1.1	0.2	0.25	0	0.0005

Upon further investigation into the diffusion mechanisms of nickel and chromium, it was found that chromia (Cr_2O_3) has been known to form both planar scale, in which good scale to metal contact occurs, as well as a convoluted, detached scale in which spalling is prominent (Stott *et al.*). This convoluted scale layer of chromia has been theorized to form because of fast short-circuit diffusion outwards, concurrent with an inward diffusion of oxygen throughout the scale grain boundaries. This mechanism would generate compressive stresses and wrinkling of the scales by creep deformation (Stott *et al.*). This could explain the pocking which occurs on grades with higher chromium content, specifically greater than or equal to 0.1wt%. Furthermore, the mechanisms related to both nickel and chromium diffusion through a metal lattice produce a scale layer which has a prominent layer of chromium underneath a thick layer of nickel oxides as seen in **Figure 4**, bringing more credibility to this chromium hypothesis.

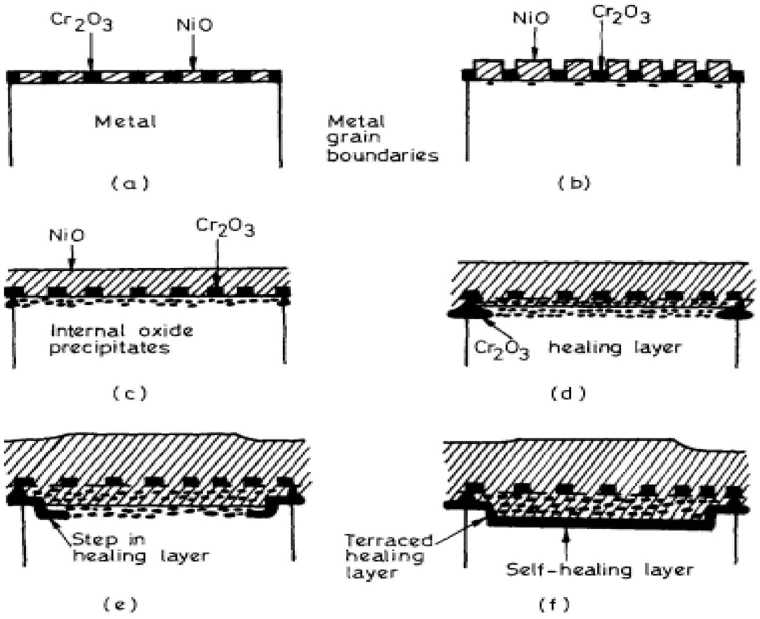


Figure 4: Schematic representation showing the progressive development of a healing chromia layer on Ni-20%Cr at 1000°C (Stott *et al.*).

The chromium hypothesis successfully predicted which grades would eventually produce feedback issues and which grades would have little issue until a specialized grade of medium-carbon steel was processed. Uncooled 10V40 steel was run through the UT equipment and displayed large amounts of background noise, similar to that of high chromium steel grades. The surface also displayed similar characteristics to that of 4140 or 8620 steel grades. This was all despite a chromium compositional range which overlapped the ranges of notably “clean running” boron and low carbon steel grades.

It was then apparent that the SBQ hot rolling process needed to be modified to alter the physical and mechanical behaviors of the scale layer. However, any change in the cooling rate of the SBQ steel brought with it the potential for alterations in the visual quality of and, more importantly, the metallurgical properties of the rolled product. Therefore, this process had to be carefully altered by trialing and subsequently testing the trialed material while carefully balancing the surface quality and metallurgical properties with the scale characteristics required for UT.

Experimental Methods

SBQ grades with acceptable UT noise levels

The low carbon (1022) and boron (10B23) grades of SBQ showed low UT scan noise. To better understand the scale on these grades, 7/32” diameter rod samples of 1022 and 10B23 steel of roughly 8 inches in length were collected and visually inspected. The two rod samples were deflected 90 degrees, plastically deforming the metal. The surface was observed under a stereoscope for both cases.

Two of the rod samples were also cut to ~1/2” in length and mounted using a clear 2-part epoxy resin. The samples were allowed to cure and were then wet ground with 180, 240, 400, and 600 grit silicon carbide paper with a warm water wash between each step, and then polished with a 9 μm and similarly a 3 μm diamond suspension until a near-mirror finish was observed. All three samples were analyzed with an optical microscope.

Hot rolling tests

To determine the optimal cooling rate, there was a plant hot rolling trial of 2” diameter 10V40 steel. Cooling rates in gallons-per-minute (gpm) of 150 gpm, 75 gpm, and 0 gpm were set to pour out of water box 1 (WB1) and water box 2 (WB2). It is to be noted, however, that a temperature re-bloom would occur after this cooling due to the higher temperature maintained at the center of the straight bar. Nonetheless, a large amount of cooling at this stage in the hot rolling process was expected to have a considerable effect on scale formation.

Firstly, the steel was rolled at normal specifications with no cooling (0 gpm). The surface appeared a typical reddish-orange with no perceivable surface defects. Secondly, the 150-gpm cooling rate was selected and a billet was taken and rolled. This cooling rate showed a surface that was visibly covered in black splotches of mill scale. Lastly, the 75 gpm was to be used, however the automated temperature setpoint software accidentally opened the water control valve of both water boxes to 100%, causing over 400 gpm to flood onto the rolled steel. The bar was almost black with surface scaling after this event.

After cooling and shipping to the processing facility, half of the bars from each of the 3 cooling regiments discussed were straightened. Every bar was then cut from a size of ~20 feet to a length of ~1 foot. Each of these samples were then cut radially into ~1-inch-thick pucks, and then divided into four pieces for mounting and analysis of the scaling, metallurgical, mechanical, and chemical properties of the steel surfaces for each of the 3 cooling regimes.

Each of the samples was hot mounted in black resin. Initial grinding was through a flight of 180, 240, 320, and finally 400 grit alumina abrasive papers. Polishing was performed with 9-µm, 6-µm, 3-µm, and finally 1-µm diamond suspensions. The polished mounts were cleaned with detergent and water to remove any residual polishing debris and were quickly rinsed with methanol and dried under a heat gun.

An analysis of surface scratching was conducted on the 0 gpm and 400 gpm samples using the Charter Steel SBQ Scratch Evaluation Form (**Figure 5**). The structure of the surface scale of all samples were then visually inspected at 100x and 500x magnification. Finally, SEM was utilized to record various atomic elements within the scaled exterior and metal surface with a focus on nickel, chromium, iron, vanadium, manganese, sulfur, and silicon.

After the visual and atomic properties of the scaled surface were analyzed, the mounted samples were etched with 5% Nital etchant. The metallurgical structure of the samples was subsequently analyzed and recorded.

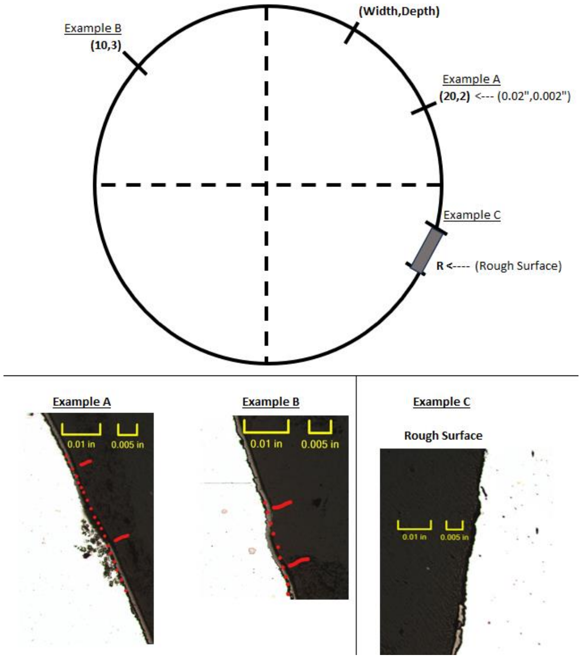


Figure 5: Charter Steel SBQ Scratching form, description page.

Verification test

A hot rolling trial 8620 steel was completed using the optimal cooling rate derived from the hot rolling tests. One 8620 SBQ bar was hot rolled with the optimal water-cooling rate and one was uncooled. Both bars were inspected by UT per plant procedures to compare feedback and noise.

Data and Results

SBQ grades with acceptable UT noise levels

The samples of 1022 and 10B23 rod product that had undergone the 90° deflection test were visually analyzed. Both appeared to have very adherent scale, as the severe deflection brought little to no appearance of flaking scale. The 10B23 sample, which included approximately 0.002% by weight boron, had a colorful sheen across the surface unlike other steel grade samples.

10B23 and 1022 are known to have very little background noise when subjected to UT. The adherent scale of these two grades appears to correlate with these clean UT results. However, the 1022 sample showed a surface of relatively thick scale along the surface, while the 10B23 boron scale, which appeared to visually display surface scale, had no apparent scale at high magnification (**Figure 6**). The lack of a microscopic scale correlates to the superior UT results seen with boron steels such as 10B23. Meanwhile, the fully adherent scale layer on the 1022 steel shows that acceptable UT results are possible with surface scaling present.

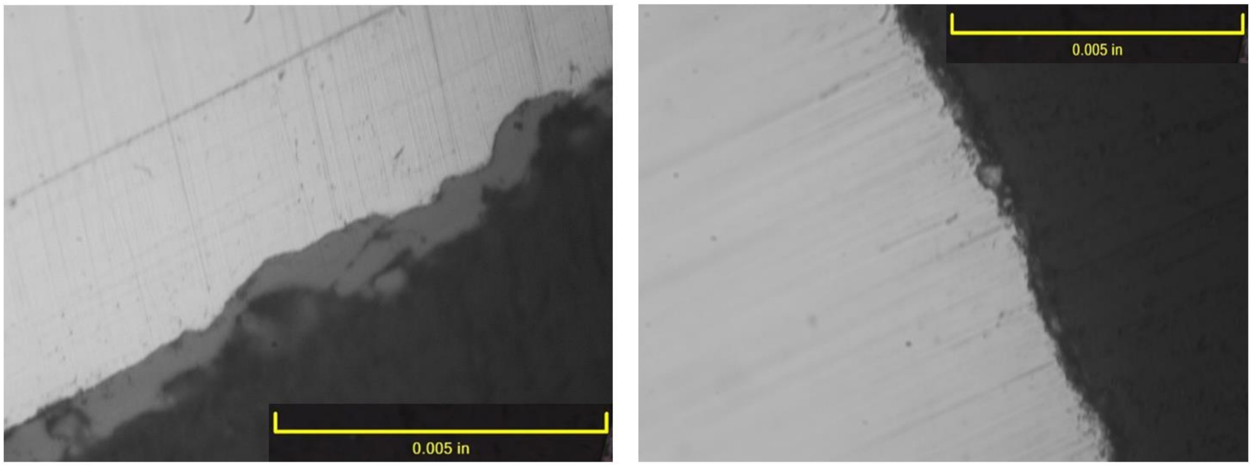


Figure 6: (A, left) 1022 scale at 1000x magnification; **(B, right)** 10B23 metal surface at 1000x magnification.

Hot rolling tests

Two sets of hot rolled 10V40 SBQ bars were examined, each containing three bars which were cooled at varying cooling rates. Of the two sets, one was straightened using the current cold rolling plant process, and the other was not. Visually, the unstraightened samples had negligible differences in surface characteristics between the 3 cooling levels (**Figure 7-9**). However, once the bars were straightened, there was a large difference in scale adherence between the 400 gpm bars and either the 0 gpm or 150 gpm bars (**Figure 7-9**). The 400 gpm samples were covered in noticeable chips and had lost half of the surface scale (**Figure 9**). Meanwhile, the 0 gpm and 150 gpm samples had very little surface abnormalities as apparent by the surface sheen (**Figure 7 and 8**).

Figure 7: (A, left) Pre-straightening 0-gpm sample; **(B, right)** post-straightening 0-gpm sample.

Figure 8: (A, left) Pre-straightening 150-gpm sample; **(B, right)** post-straightening 150-gpm sample.

Figure 9: (A, left) Pre-straightening 400-gpm sample; **(B, right)** post-straightening 400-gpm sample.

Scale characteristics

The 10V40 scaling characteristics of the tested, unstraightened SBQ bars were optically inspected at 100x and 500x magnification. The 0-gpm samples showed poor adhesion between the metal oxide and metal surface (**Figure 10**). Furthermore, the metal oxide layer contained air pockets on the order of 1 mil (0.001 inches), seen as the dark areas within the scale on **Figure 10B**. The 150-gpm sample was similar in terms of scale adhesion yet showed far less porosity than the 0-gpm sample (**Figure 11**). Finally, the 400-gpm scale showed a further reduction in porosity and displayed great adhesion to the metal surface (**Figure 12**).

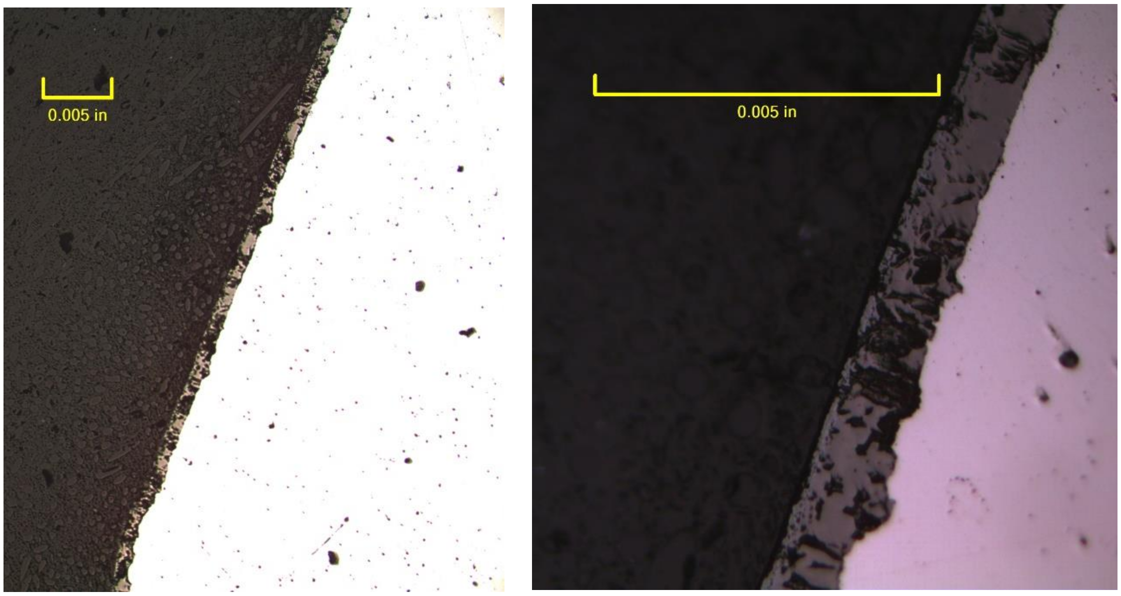


Figure 10: (A, left) 0-gpm cooling regime at 100x magnification; **(B, right)** 0-gpm cooling regime at 500x magnification.

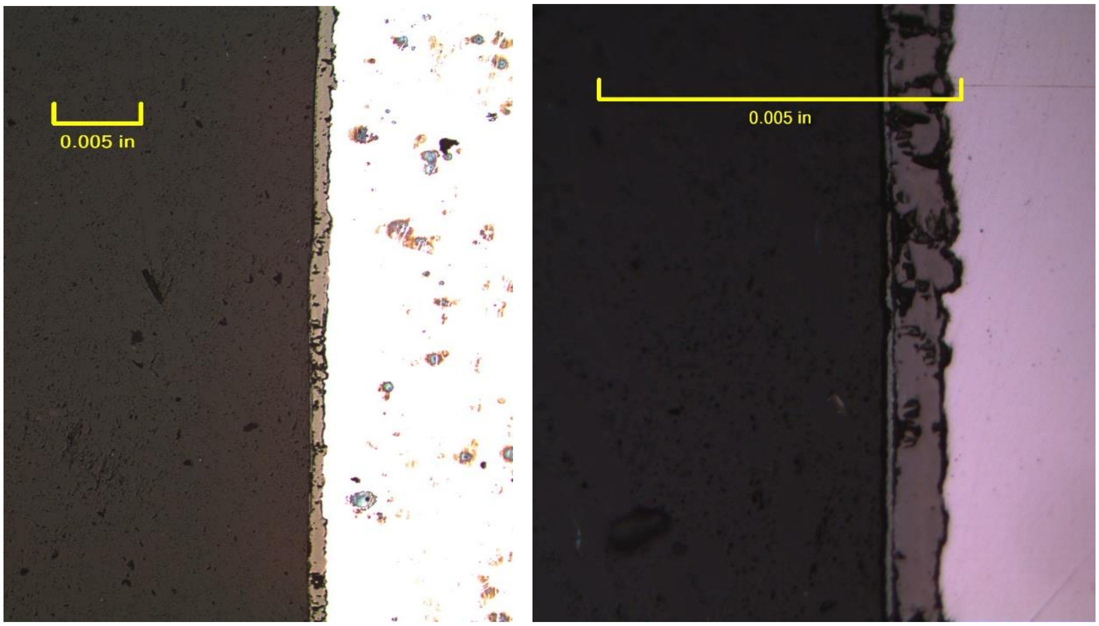


Figure 11: (A) 150-gpm cooling regime at 100x magnification; **(B)** 150-gpm cooling regime at 500x magnification.

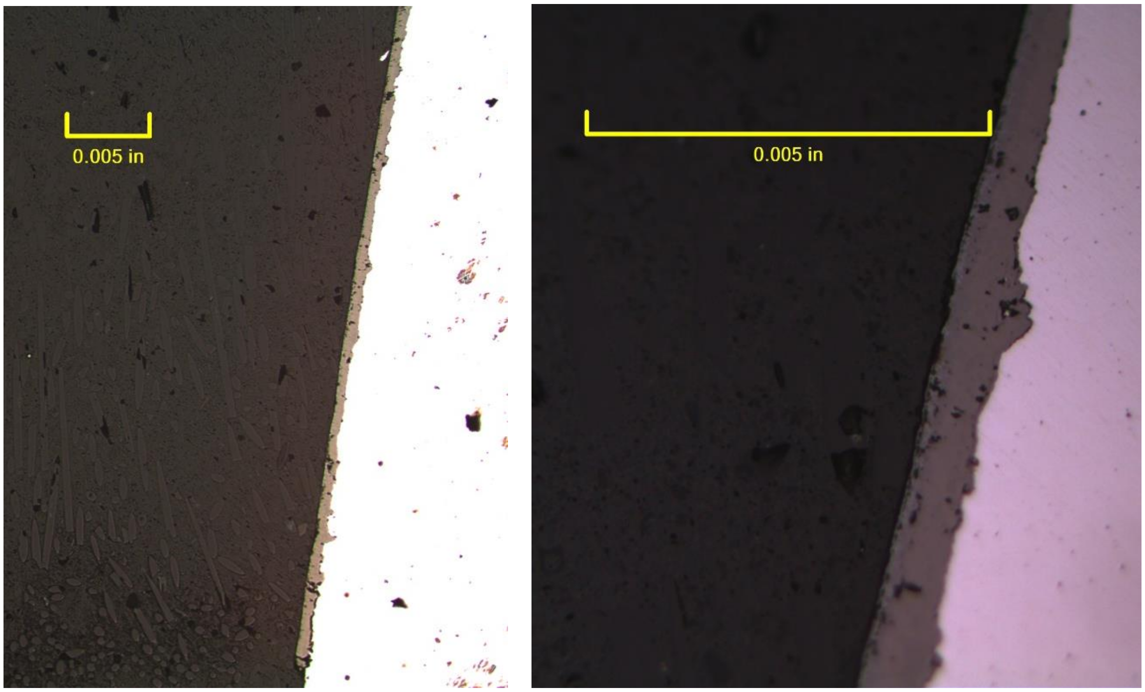


Figure 12: (A, left) 400-gpm cooling regime at 100x magnification; **(B, right)** 400-gpm cooling regime at 500x magnification.

Microstructural characteristics

The samples were etched and examined under an optical microscope to determine the metallurgical characteristics of the unstraightened SBQ bars. The 0gpm and 150gpm samples showed little difference in their microstructure (**Figure 13**&14). Meanwhile, at the highest cooled portion of the surface, the 400gpm sample showed a bainitic character within the outer 8 mils of the metal, as opposed to the typical fine fine-grained pearlite structure (**Figure 15&16**).

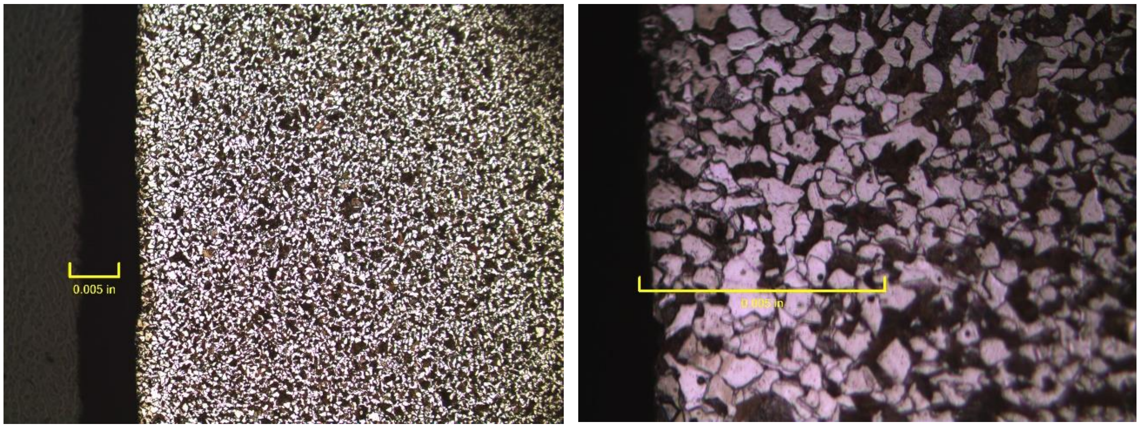


Figure 13: (A, left) 0-gpm surface metallurgy at 100x magnification; **(B, right)** 0-gpm surface metallurgy at 500x magnification.

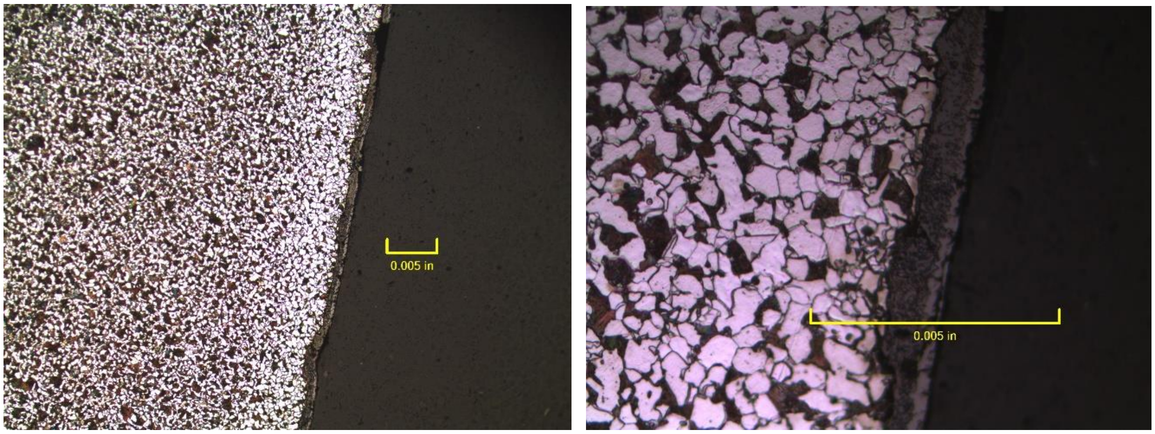


Figure 14: (A, left) 150-gpm surface metallurgy at 100x magnification; **(B, right)** 150-gpm surface metallurgy at 500x magnification.

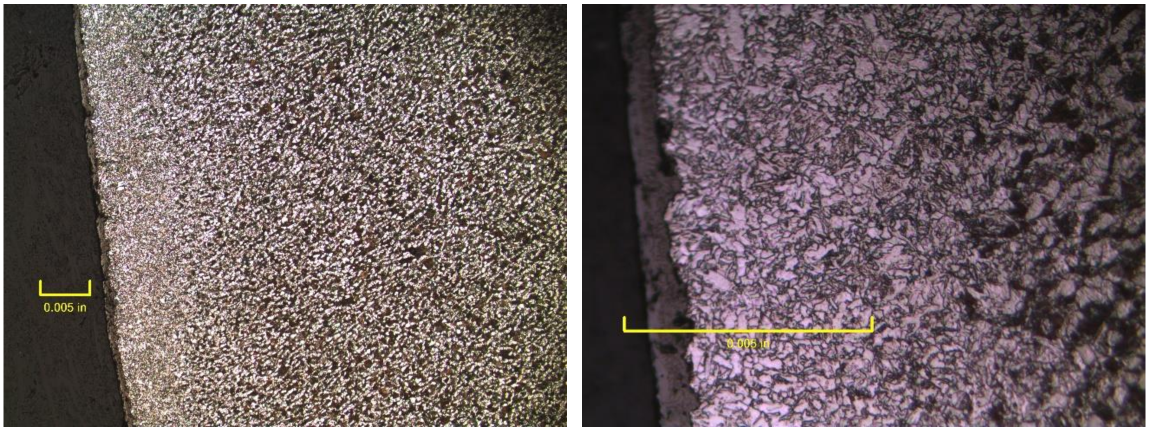


Figure 15: (A, left) 400-gpm surface metallurgy at 100x magnification; **(B, right)** 400-gpm surface metallurgy at 500x magnification.

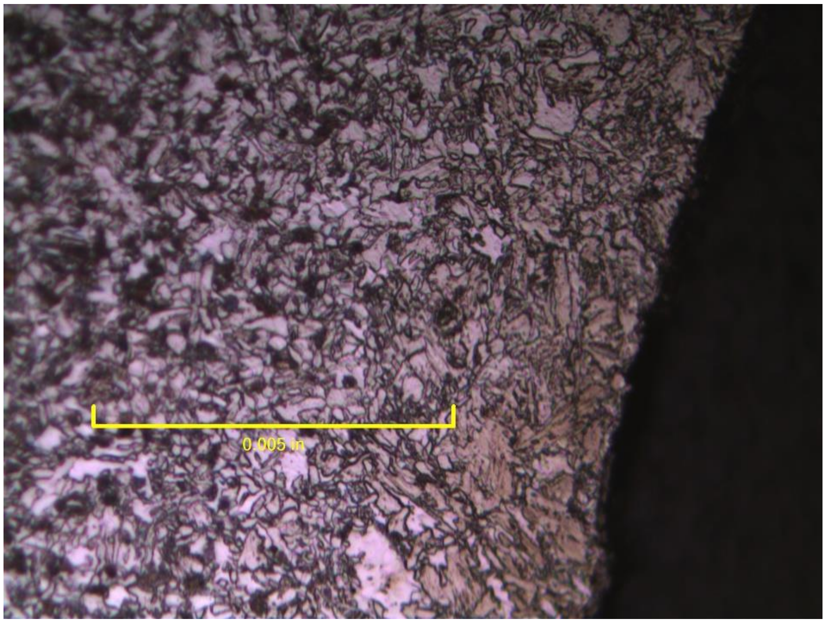
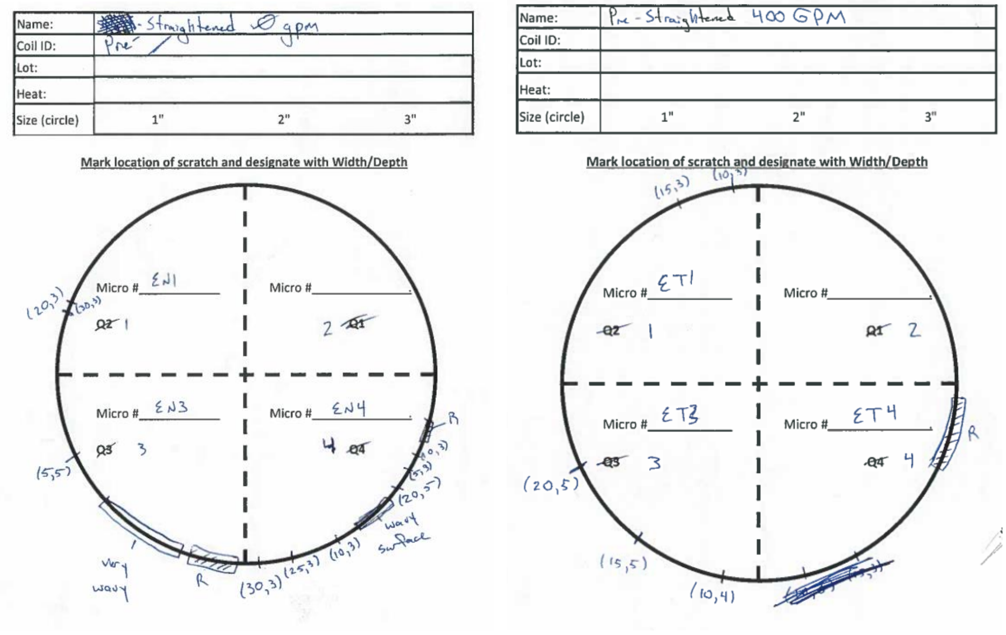


Figure 16: 400 gpm surface metallurgy at 500x magnification showing bainitic structure.

Surface characteristics

The appearance of the product is important to many customers. SBQ bars that contain surface scratches lower the level of quality in the customer's eye. The plant's scratching characterization procedure was used to assess unstraightened samples from the 0 gpm and 400 gpm cooling regimes. The results from the scratch characterization procedure are shown below for 0 gpm and 400 gpm. There are relatively fewer scratches along the surface of the 400gpm sample compared to the 0gpm sample. Furthermore, the scratches are far shallower on the 400gpm sample, displaying a correlation between higher cooling rates and higher surface hardness.



Name:	~~[illegible]~~-Straightened 0 gpm		
Coil ID:	Pre-		
Lot:			
Heat:			
Size (circle)	1"	2"	3"

Mark location of scratch and designate with Width/Depth

Micro # EN1
~~Q2~~ 1

Micro #
2 ~~Q1~~

Micro # EN3
~~Q3~~ 3

Micro # EN4
4 ~~Q4~~

Name:	Pre-Straightened 400 GPM		
Coil ID:			
Lot:			
Heat:			
Size (circle)	1"	2"	3"

Mark location of scratch and designate with Width/Depth

Micro # ET1
~~Q2~~ 1

Micro #
~~Q1~~ 2

Micro # ET3
~~Q3~~ 3

Micro # ET4
~~Q4~~ 4

Figure 17: (A, left) 0 gpm scratch characterization and **(B, right)** 400 gpm scratch characterization.

Subsurface Characterization

Finally, unstraightened 10V40 samples of all 3 cooling regimes were inspected by SEM imaging. Initial SEM imaging did not display a gradual difference between the 3 steel sample types. As seen in **Figure 18A&B**, the SEM did not yield photos of high enough accuracy in order to make any decent conclusions as to the diffusion behavior of the alloying agents. However, success was found within an SEM image mistakenly taken of silicon on a 150gpm sample. **Figure 19A** displays a large concentration of silicon within the M/MO interface.

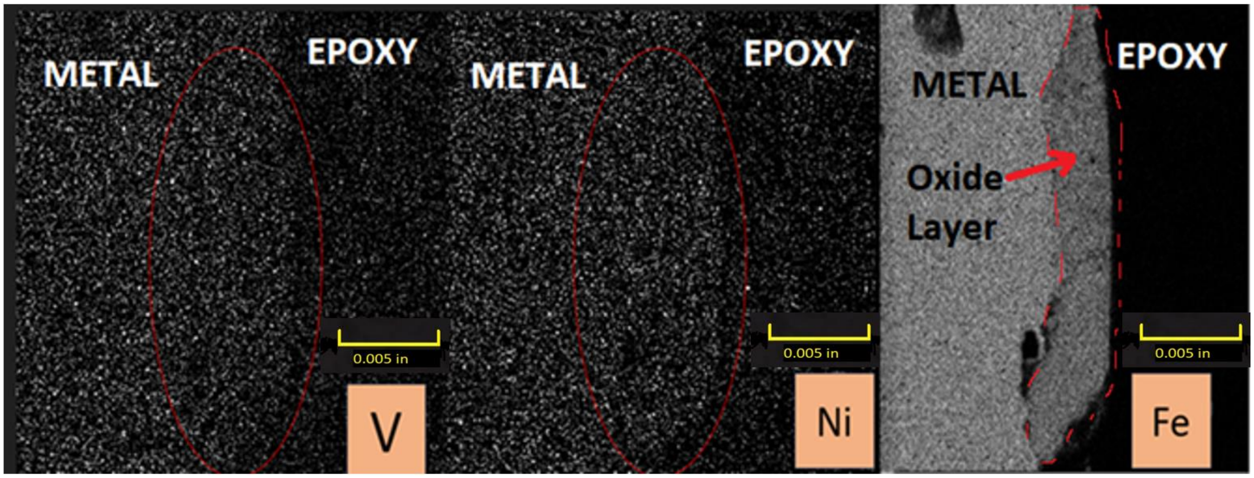


Figure 18: (A, left) Vanadium and **(B, middle)** Nickel SEM imaging besides that of **(C, right)** iron. Note, the darker grey area shown in the iron scan is iron oxide.

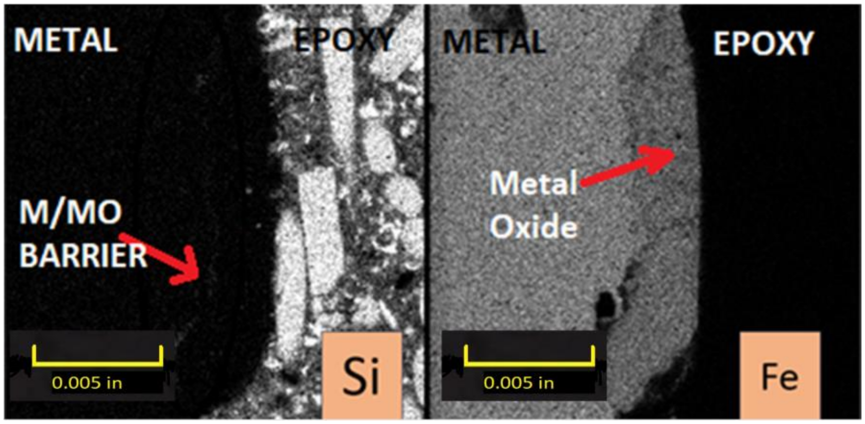


Figure 19: SEM scan of **(A, left)** silicon, with the red circle displaying the presence of silicon along the M/MO barrier, and that of **(B, right)** iron.

A second array of SEM imaging was conducted to understand the diffusion pattern of silicon under all 3 of the cooling regimes. This yielded three images, which display the correlation between lower cooling rates and higher silicon concentration at the M/MO interface (**Figure 20**).

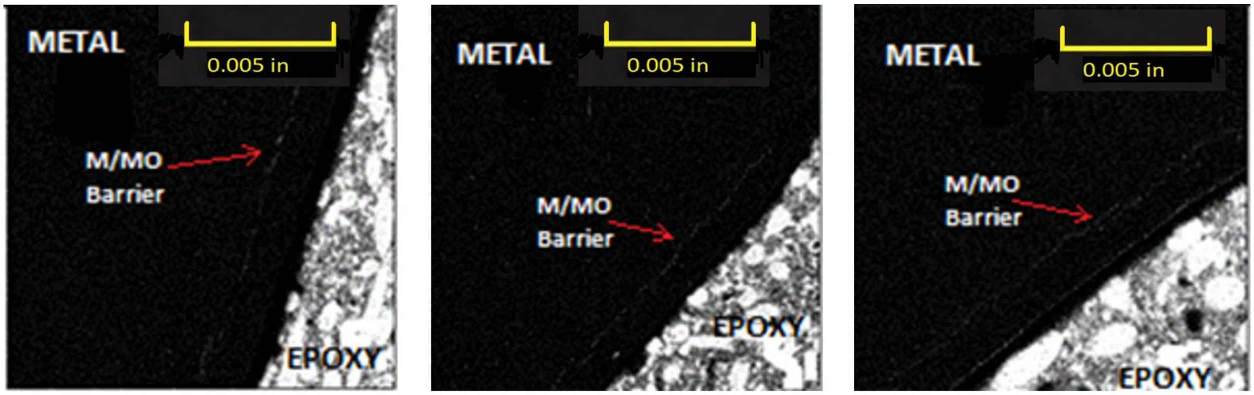


Figure 20: (A, left) SEM scan of silicon for 0-gpm cooling; **(B, middle)** SEM scan of silicon for 150 gpm cooling; and **(C, right)** SEM scan of silicon for 400-gpm cooling.

Verification tests

Based on the results of the previous trial, a second trial was conducted using a water cooling rate of 300 gpm for the hot rolling of 8620 SBQ. One bar was uncooled (0 gpm) and another bar cooled with a 300-gpm water flow rate. Both were analyzed by UT, with the results showing a large decrease in UT background noise by utilizing an increased cooling rate (**Figure 21**).

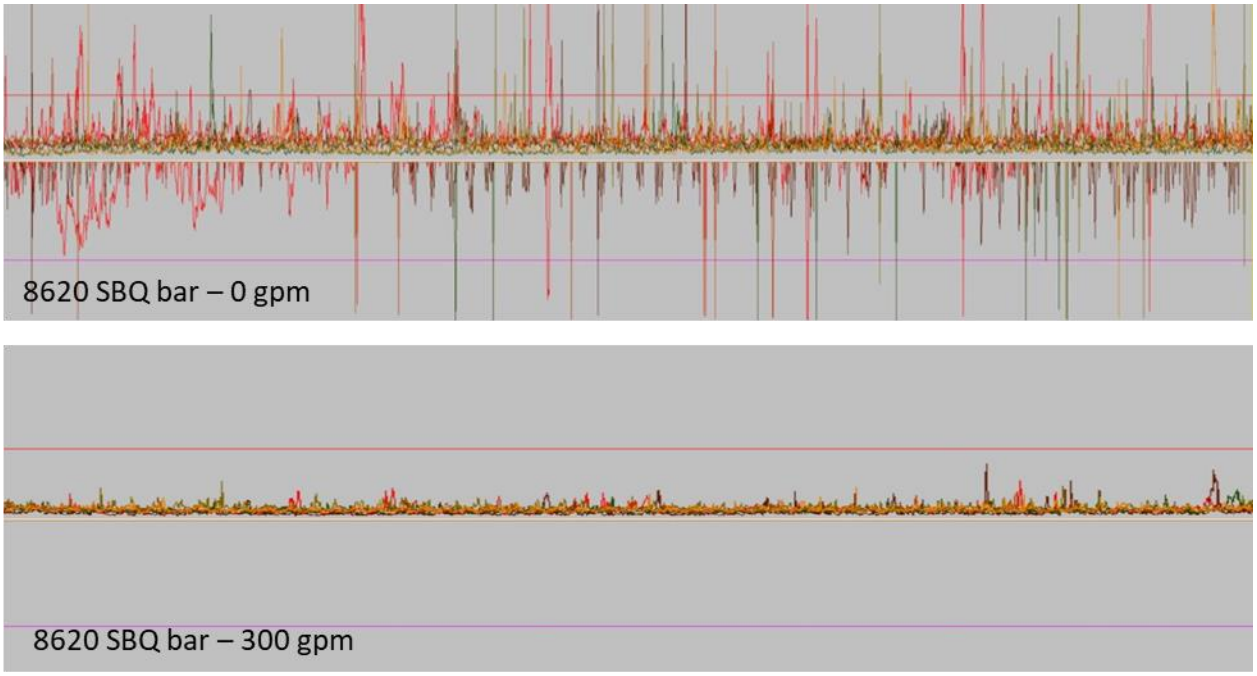


Figure 21: The uncooled 8620 SBQ bar UT scan has too much noise to be used for quality analysis; **(top)** water cooling at 300-gpm during hot rolling eliminates most of the noise **(bottom)**.

Discussion and Analysis

SBQ grades with acceptable UT noise levels

Deflection experiments of hot rolled 1022 and 10B23 grades showed little to no scale spalling. Despite their similar carbon content (**Table 1**), the surface scales of 1022 and 10B23 were different in visual appearance. 1022 had a typical dull surface, while 10B23 had a shiny and somewhat colorful sheen on its surface. Microscopic examination showed that 10B23 lacked microscopically visible surface scale, while 1022 had a thick and adherent surface scale. It is assumed that the colorful sheen of 10B23 comes from a nano-scale oxide layer on the surface of the metal.

The lack of an iron-based scale layer on 10B23 is likely due to the formation of iron borides at the M/MO interface. Boron is also known to work as an effective flux for glass-forming by dissolving various types of metal and nonmetal oxides (E Vernaz *et al.*). Iron borides additionally exhibit very brittle characteristics, making them highly susceptible to spallation (Y Gou *et al.*) as well as promoting grain boundary cracking (R Wang *et al.*), so it is understandable that a boron steel would lack most, if not all, of its surface scale and therefore lack any considerable background noise when ultrasonically tested.

Hot rolling tests

Adhesion characteristics

The difference in scale adhesion shown between 400-gpm and 0-gpm or 150-gpm cooling rates is considerable. Nonadherence of the metal oxide at 0 gpm and 150 gpm rates to the metal surface helps to explain the relatively higher noise of the uncooled and partially cooled steel grades.

The relative porosity of the 0-gpm sample also gives a better understanding of prior observations of the surface scaling as being “powdery.” A porous, nonuniform layer of scale will also crumple into small particles when exposed to high pressures experienced during straightening as opposed to coming off in large slabs as a uniform, nonporous scale would. This explains the dramatic difference in visual appearance between the 0-gpm sample in **Figure 7B** and the 400-gpm sample in **Figure 9B**, as the cracking and failure mechanisms of the two oxide layers differ greatly. Furthermore, simple corrosion of the iron to form iron oxide scales ranging from wustite or magnetite to hydrated hematite (otherwise known as rust) would be further aided by the porous nature of the scale, creating a powdered scale as seen in **Figure 3B**.

Microstructural characteristics

A relatively large metallurgical difference was not seen between the 0-gpm and 150-gpm samples, with both displaying mostly coarse fine-grained pearlite. However, the 400 gpm samples showed a large change in the typical surface crystallization seen in SBQ. A surface of fine fine-grained pearlite was observed over most of the bar’s surface, while one area (shown in **Figure 16**) displays bainitic character. These atypical grain structures were only located within ~8 mils of the surface and transitioned to the aforementioned coarse fine-grained pearlite regime throughout the rest of the microstructure.

These crystalline structures help to visually identify the cooling volume at which rebloom (in which the core of the SBQ reheats the surface) does not entirely recrystallize the structure and reheat to a temperature at which scale formation can occur to the extent of uncooled steel product. The most likely cause of the minimal difference between 0 gpm and 150 gpm is the Leidenfrost effect, in which high pressure steam pushes liquid water away from the metal surface, reducing the cooling capacity of the water box. A cooling volume above 150 gpm must be utilized to overcome this effect and attain a scale formation as seen in **Figure 12B** on the 400-gpm sample.

Fortunately, such metallurgical characteristics on the outer surface of the SBQ product do not fall outside of most customer specifications due to typical surface annealing and full annealing practices that are performed once it is received by the customer. Furthermore, a slight reduction in cooling rate will most likely result in a significant lack of surface bainitic transformation whilst maintaining the surface scaling characteristics of the experimental 400gpm cooling rates if harsher specifications are to be met.

Surface Characteristics

The cooling of the SBQ at 400 gpm creates a considerable reduction in surface scratches, most likely due to the increased hardness attained by the cooled steel. Therefore, in addition to an increase in UT ability, the visual surface quality of the SBQ product is also improved.

Despite the negligible effect that SBQ surface quality has on manufactured parts, it is nonetheless a sought-after specification for many customers. Reducing the visual scratching will greatly improve the ability of Charter Steel to sell orders to a more diverse group of customers.

Subsurface characteristics

The SEM analysis shows that a higher volume of water cooling will result in a M/MO barrier with a more uniform distribution of silicon and silicon oxides while no cooling displays a M/MO barrier with a much higher concentration of nonuniformly dispersed silicon and silicon oxides. Furthermore, the areas of higher silicon concentration appear to align with scale spalling, as seen in **Figure 19A**.

It has been remarked by F.H Stott that steels with high concentrations of chromium and silicon (26% and 1% respectively) can cause the formation of a porous chromia and iron oxide scale layer with a band of precipitated silicon oxides at the M/MO barrier. Furthermore, this silicon oxide layer is relatively brittle and promotes scale spalling when deformed. (Stott et al.)

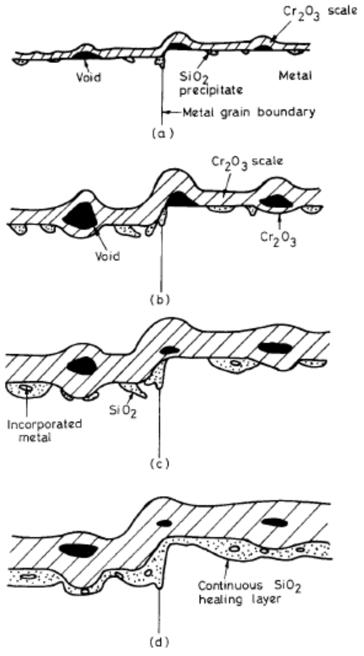


Figure 22: Silicon and chromium scaling mechanism at high alloying concentrations in steel (Stott *et al.*).

It is now understood that a similar phenomenon is occurring in many of the SBQ steels, despite a lower alloy content. Higher cooling rates were influencing the ability of silicon to diffuse into the M/MO barrier, creating less porosity and promoting greater adhesion. This occurs because silicon is unable to oxidize and form as readily as metals such as nickel or chromium. Meanwhile, chromium is unable to cause buckling and later void formation due to decreased diffusion rates, caused by the decrease in temperature from cooling. Furthermore, nickel additions are known to promote uniform scale adhesion, while silicon decreases scale adhesion in a non-uniform manner. Therefore, nonuniform scale adhesion occurs in which microscopic air pockets are trapped, creating UT echoing. Chromium, as discussed earlier, promotes porosity throughout the scale, and thereby protects the underlying air pockets formed by the nickel/silicon phenomenon.

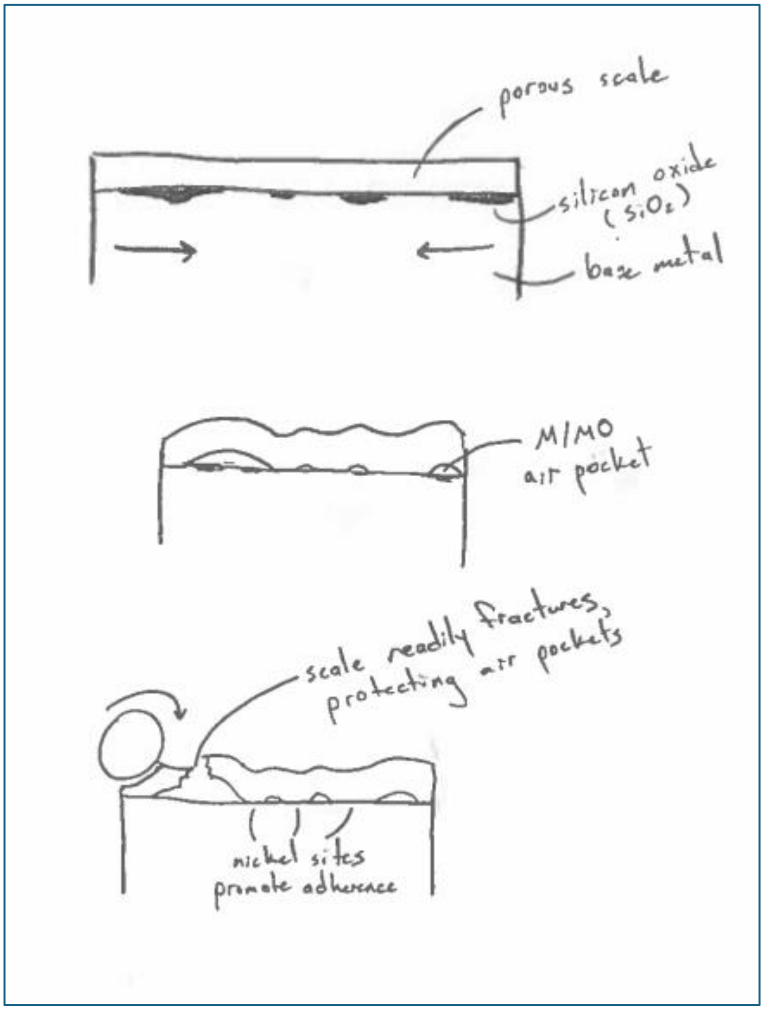


Figure 23: Proposed silicon-nickel-chromium scale phenomenon.

When considering the nominal concentrations seen in **Table 1**, a silicon content of 0 to 0.1wt% is the range given for 1010 low carbon steel. Additionally, when looking at previously captured images of low carbon steel, a nonporous and continuous, albeit a worn scale layer is apparent on the surface (**Figure 24**).

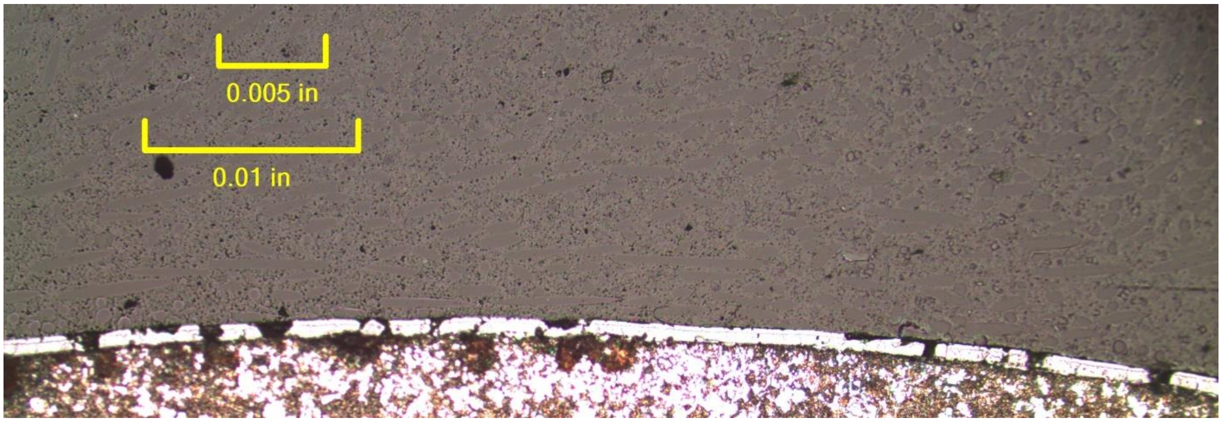


Figure 24: Example of a low carbon steel surface.

Meanwhile, all other steel grades apart from Boron steels which have displayed issues in UT testing have a silicon minimum of 0.15wt% or higher. Therefore, it is concluded that a silicon content of greater than or equal to 0.15wt% will create a nonadherent scale layer when the steel is hot rolled without water cooling, unless there is a boron addition.

Verification test

Once subjected to UT, the 300gpm cooled 8620 SBQ showed a remarkable decrease in noise when compared to uncooled 8620 SBQ. Although differing from 10V40 metallurgically (**Table 1**), it is seen that the similarities in silicon content allowed the scaling characteristics of 8620 to be similarly altered by cooling. Furthermore, the lower cooling rate of 300gpm as opposed to 400gpm would most likely see less bainitic transformation along the surface of the bar, improving metallurgical homogeneity and, therewith, quality.

Meanwhile, the revelation of the effects of silicon content on porous scale formation will greatly increase the productivity of the Charter Steel facility as a whole. Steels that contain 0.15wt% or higher in silicon and lack boron above trace levels will now be cooled at a rate of 300gpm or higher from both SBQ water boxes if UT specifications are to be met. Alongside the added benefit of increased surface quality, these new abilities stand to offer a more diverse customer base, including companies which require more rigid specifications.

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