HIGH QUALITY PRODUCTION OF NIOBIUM MICROALLOYED STEELS[1]

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Abstract

Several key operational and metallurgical parameters must be properly balanced for the successful production of high quality niobium microalloyed steels. Over 200 million tonnes of niobium (Nb) microalloyed steels were produced last year globally across the automotive, pipeline and structural segments. The production of these defect free continuously cast microalloy Nb steel slabs, blooms and billets have increased in importance for both the producer and the end user. The minimization of surface and internal defects has a substantial impact on steel producing operating costs, internal and external cost of quality and delivery performance. There are universal fundamental operational and metallurgical principals when producing microalloyed steels regardless of the caster or mill configuration, equipment capabilities or layout. In addition, the proper slab selection, reheating parameters and practices, automatic or manual generated rolling schedules, carbon and alloy design, reduction schedules and overall proper process design affect the operational cost effectiveness. The interaction of these factors will govern the resultant hot roll surface quality and mechanical properties. This paper will present common as-cast and hot rolling defect characteristics, proper identification of such defects, cause and effect relationships, and corrective actions and will describe key casting, hot rolling operational/metallurgical parameters related to surface quality that need to be considered when producing all steels in addition to niobium microalloyed steels. It is extremely important that the proper identification of surface quality issues is determined so that the proper corrective actions can be employed. Steelmakers around the world who understand and implement this root-cause analysis and corrective action system increase their probability of successfully resolve their surface quality related issues.

Key words: Casting; Defect identification; Hot rolling; Root-cause analysis.

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1 INTRODUCTION

The increased demands of design engineers require the development of proper alloy/processing designs at an economical cost in steel production. Complex chemistry designs and hot rolling schedules for any carbon steel alloy design makes the processing more challenging, especially when process metallurgy variables are not in control. Both improper alloy designs and processing parameters can result in surface quality related issues in the as-cast and/or the final rolled product. Some steelmakers have related surface quality issues in the final as-rolled product to the microalloy design technology and hence, incorrectly conclude that the design is the root-cause problem. Under these circumstances, process-control variations at the Basic Oxygen Furnace (BOF) or Electric Arc Furnace (EAF), continuous caster or rolling mill may in fact be the root cause of the poor slab, billet or surface quality. In contrast, over 200 million tonnes of Nb microalloyed steels were successfully produced last year at numerous steelmakers around the world.

Surface quality related issues in a final as-rolled plate, sheet or bar often result from the melting and/or continuous casting processes. Longitudinal and transverse cracks, edge cracks, slivers, seams and scabs may be evident on the slabs, billets or blooms before rolling or appear after the hot rolling process. Proper identification of the final as-rolled defect involves an understanding of the cause effect relationship between the surface defects characteristics and the process control parameters that cause the defect. Proper investigation studies the appearance, shape, size and sometimes chemistry of the as-rolled defect, thereby providing valuable information for identification of the cause-effect relationship and implementation of proper corrective action.

2 SURFACE QUALITY RELATED ROOT CAUSE ANALYSIS AS-CAST SURFACE DEFECTS

Five major categories of surface defects are typically observed in a slab or billet that result in final as-rolled surface defects,(1) Table 1. Based upon experience, these five major categories and the frequency experienced (from highest to lowest) are:

- pinholes/porosity is the number one cause of final as-rolled surface quality defects, but it is the one that is most overlooked and ignored;
- cracks can fall into three classifications, longitudinal, transverse and star cracks. This is the second major cause of final as-rolled surface quality issues and receives the most attention and research. Also, cracks are the most misidentified defect which accounts for final as-rolled surface quality issues;
- deep casting oscillation marks are the third most common issue and can manifest themselves into looking like cracks in the final as-rolled plate and hence, are improperly identified as coming from as-cast cracks;
- poor scarfing is number four and less common, but can create as-rolled surface defects that get the improperly categorized as initiating from as-cast cracks that are often overlooked and operationally induced;
- mechanical mold wall contamination, scratches and gouges are the final major category and the least common.

An understanding of these five categories and defect location on the slab and hot rolled product is necessary in order to properly identify the correct defect and develop the proper corrective actions. The oxidation (scaling) of the external defect during the reheating of the slab/billet will ultimately determine the critical depth of which a slab/billet surface defect will become a rolled plate, coil, or bar surface defect.

Table 1. Five Categories of As-cast Surface Defects in Order of Frequency Experienced

Slab/ Billet Defect Type	**#1 - Pinholes/ Porosity**	**#2 - Cracks**			**#3 - Deep Oscillation Marks**	**# 4 – Poor/ Improper Scarfing**	**#5 - Mechanical Mold Wall Contamination, Scratches, Gouges, etc.**
		Longitudinal	**Transverse**	**Star**			
Location	Predominately on top one or both corners can be in top body as severity increases. Generally not on the bottom but can be in vertical mold casters	Predominately on top or bottom body, sometimes in the corners	Predominately on top edges/corners. Occasionally on bottom corners depending on caster type and condition. Can also be in the body, but not as common.	Top and bottom body surface	Top and bottom randomly located dependent on casting machine and parameters.	Generally top and bottom edges. Can be random in body depending on scarfing required.	Randomly distributed top and bottom

3 DETAILED DISCUSSION OF TYPICAL AS-CAST SLAB SURFACE DEFECTS

3.1 Pinholes/Porosity

The most common slab/billet defects most casters encounter and often overlooked are surface pinholes/porosity. Depending on the rolling sequence (straight away vs. broadside rolling) for producing the product width, the diameter of the pinhole/porosity along with the final product thickness or diameter (for bar) will determine final geometry or features. Examples of slab pinhole/porosity exposed by scarfing and resultant plate/coil defects are illustrated in Figure 1.

Pinholes below the narrow face surface and 10-12 mm below top broadface corner

Large pinholes on top broadface near corner. Note the largest pinhole is ~ 3-4 mm in diameter.

Numerous pinholes on top broadface in the body of the slab

Straight away rolled light gauge at edge

Straight away rolled heavy gauge at edge

Broadside rolled heavy gauge in body

Figure 1. Example of slab pinhole/porosity defects by rolling logic and gauge.

3.2 Cracks – Longitudinal, Transverse, Star

Longitudinal and transverse cracks are the second most common surface defect found on continuously cast slabs/billets. Longitudinal cracks are less common than transverse cracking with good steelmaking practices. Longitudinal cracks can be shallow or deep and are typically in the body of the slab, but can be near the edges in some situations. They are located on either top or bottom (Figure 2). Longitudinal cracks can sometimes be seen as dark lines on the as-cast slab surface as the slab exits the caster.

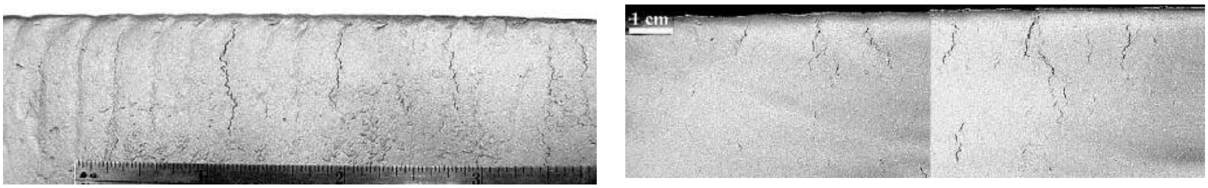
Example of various longitudinal slab cracks

Straight away rolled longitudinal slab crack

Figure 2. Example of longitudinal slab cracking.

The majority of the longitudinal cracks will roll out appearing as a long seam-like defect, especially if straight away rolling is employed (Figure 2). If broadsiding is used then the longitudinal crack will exhibit some width, but will still have similar features to that of a slab rolled straight away.

Transverse cracking is typically located on the top near at the edges of the slab or billet. In more severe cases they can be located in the body of the slab/billet. They are typically on the top as they are usually associated with low ductility trough associated with temperature that may result in cracking during the unbending of the slab/billet through the straightening section. However, based upon recent research, the reduced reduction in area at straigthening temperatures through the unbending section are more related to the melting and casting operational parameters than the inherent ductility trough of microalloyed steels.(2) Figure 3 shows transverse cracks found on the top of the slab at the corners in both the scarfed and un-scarfed condition.(3) These types of cracks can be very small and difficult to see with the unaided eye on the as-cast slab/billet surface. Hence, scarfing is the best tool to inspect for these types of cracks.



Top edge slab transverse cracking – as-cast

Top edge slab transverse cracking - scarfed

Figure 3. Example of top edge slab transverse cracking.

Transverse cracks can roll out looking like those created by pinholes/porosity regardless of rolling logic (straight away vs. broadside rolling) due to their geometry.

Star cracks typically form from grain boundary embrittlement from mold contamination (Cu pick up from the mold) or oxidation. They form on the slab/billet face were the mold contamination may occur. Figure 4 shows an example of a star crack.(4) Star cracks use to be fairly prominent issue in casting, however with the technology and understanding of the causes of these types of cracks, today they are virtually none existent.

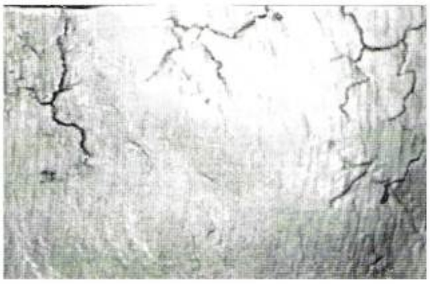


Figure 4. Example slab star crack

3.3 Oscillation Marks

All continuous cast slabs/billets have some degree of oscillation marks located on the surface. Depending on the caster, casting speed, the oscillation stroke and the heat transfer, the depth and frequency of these marks will vary. In general, these typically do not cause issues as they are very shallow and will oxidize off in the scale during heating in the furnace. However, if process parameters get out of control and the oscillation marks are very deep, and then transverse cracks can from within the oscillation mark. When the oscillation marks are deep, they alone can cause surface defects. In addition, an oscillation mark can be a stress riser when coupled with the inherently weak ferrite film formation along the prior austenite grain boundary can result in transverse cracking as illustrated in Figure 5.

Figure 5. Example of transverse crack formation starting at the base of an oscillation mark and then following the prior austenite grain boundary ferrite film and mild oscillation marks.

3.4 Poor Scarfing

Scarfing is an excellent tool following inspection for the removal of slab/billet surface defects on continuously cast slabs. However, the technique does require skill to be mastered to be able to properly scarf without creating additional surface defects on the final product. Deep gouges, ridges from scarfing will and cause potential surface quality issues in rolled plate and coil (Figure 6). If proper scarfing is not performed properly, then the defect tends to fold over on itself and roll out looking like a very straight scratch or longitudinal type surface crack. In addition, grades with carbon equivalents (CE) ≥ 0.50 as measured by the IIW - Dearden O'Neill formula CE(IIW/DO) = %C+%Mn/6+((%Cr+%Mo+%V)/5)+((%Cu+%Ni)/15), have a tendency to thermal crack upon introduction to the heat from scarfing and new defects may be created. An example of thermal surface cracking from scarfing a slab cold on the top surface of a high CE grade (0.73) plate can be seen in Figure 6.

Example of poor scarfing technique, too steep

Example of straight away rolled scarfing defect from poor edge scarfing technique

Example of poor edge scarfing technique that can result in plate edge defects, corner too sharp

Example of plate edge defects that can be created by poor scarfing technique

Example of thermal shock cracking on the top surface of heavy gauge rolled plate from cold scarfing of high CE slab

Figure 6. Example of improper and proper scarfing along with plate defect from scarfing.

3.5 Mechanical Mold Wall Contamination, Scratches, Gouges

There are numerous mechanical issues that can occur during the casting and handling of slabs/billets. However, in general these are typically very rare occurrences. An example of mold wall contamination can be seen in Figure 7.

Figure 7. Example of surface defects from hot shortness caused by copper contamination from casting mold. Note this is not the same type of defect as seen in star cracks.

4 INVESTIGATION OF SURFACE DEFECTS

Many steel facilities try to identify the as-rolled surface defect and then assume the root cause without properly identifying which defect was responsible for crack initiation. This type of fractographic analysis is very difficult and requires many years of experience in order to properly assess and correlate the rolled defects versus the cast defects. The best approach to investigation involves a proactive inspection of the slab/billet surfaces. The most successful approach to this inspection is through the use of gas/flame scarfing of selected slabs/billets within the casting sequence. This requires that the personnel performing the scarfing are properly trained to identify the various types of defects as discussed prior. This is where mills tend to make mistakes in the improper training of scarfing/inspection personnel. In most cases, the slab defects noted above tend to be in certain slabs of the sequence. The probability of surface issues tends to be the highest in the first and last slabs cast in the sequence followed by the first and last slabs involved in the ladle exchange. So at a minimum, an inspection routine can be carried out on these slabs with some random inspections throughout the sequence. Slabs/billets involved in casting process parameter deviations such as sudden changes in mold speed, mold level fluctuation, nozzle clogging, etc. should also be inspected. A preferred inspection scarfing pattern should be robust enough to identify problem areas of the slab to highlight the defects discussed. This practice should be done on both the top and bottom of the selected slabs/billets. The inspection program should be such that if something is identified in the inspected slab/billet, slabs/billets on each side of that slab during casting, should be inspected as well until the defect can no longer be seen. However, by understanding the probability of where the slab/billet defects might be located (top vs. bottom, edge vs. body etc.) and the probability of the various defect types and geometry of the rolled defect by rolling sequence can assist in the determination of the type of slab/billet defect present. The analysis involves a methodical process of elimination linking the identified defect to the root cause origin. In addition, metallography can help in determination between a rolled surface defects vs. a surface defect that came from a slab/billet. Actual examples of various defects under metallographic examination can be seen in Figure 8.

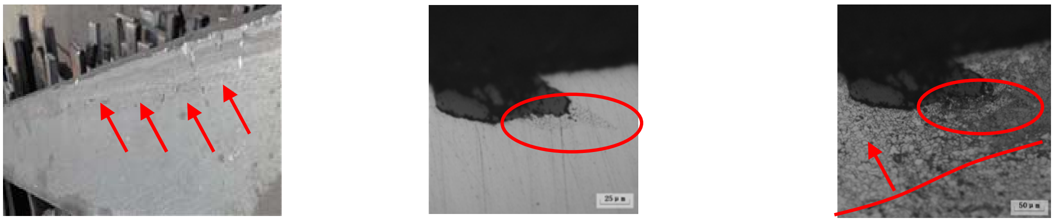
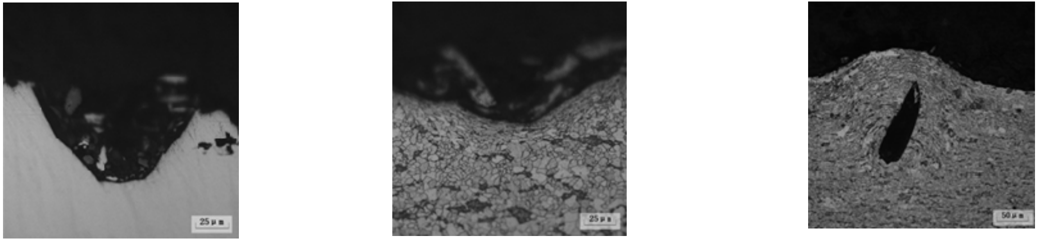


Plate edge surface defects analyzed by metallographic technique.

Note oxides in red circle evidence of slab defect that was partially exposed during the reheating of the slab. Most likely a partially subsurface pinhole in the slab

Same defect except now etched to show decarburization (low carbon ferrite) layer, red line. Oxides still seen in red circle area.



Scratch from rolling operation; note the lack of any oxides which is typical of rolling induced defects.

Pressed in surface defect from rolling, note deformed grains following defect in decarburized zone. Note the lack of oxides which is typical of rolling induced defects.

Large non-metallic inclusion from slab corner near edge, note the inclusion turning during rolling and subsequent raised surface and metal flow lines showing inclusion movement.

Figure 8. Examples of various plate surface defects under metallographic examination.

5 SLAB/PLATE/COIL SURFACE DEFECTS MITIGATION CONTROLS

5.1 Basic Oxygen Furnace, Electric Arc Furnace Steelmaking and Casting Considerations

Based upon comparisons of Basic Oxygen Furnace (BOF) or Electric Arc Furnace (EAF) steelmaking and operational practices at different steel mills around the world, experience indicates most mills are consistently producing defect-free Nb microalloyed slabs, billets and/or beams Those mill encountering quality issues will benefit from the presented root cause analysis methodology and case examples. Also, operational experience concludes that mills consistently casting defect-free high surface quality microalloyed steels also exhibit an overall better quality rating across their entire product mix.

Mills encountering difficulties typically turn to the ductility trough argument as the reason for the problem. Much has been published regarding the ductility trough topic for simple carbon-manganese steels and microalloyed steels, which is an inherent property of various chemistry steels. For example, often the hot ductility characteristics of the cast steel is attributed as the root cause of surface cracks, when in fact, process control is the real root cause. Also, a lack of properly identifying the defect (Table 1 in the previous section) leads to an incomplete mis-identified corrective action.

Global research, development and root cause analysis involving surface cracking that occurs during casting, is often related to the following process parameters not in control for a given heat. These factors relate to:

- residual chemistry (Hydrogen, Nitrogen, Oxygen);
- superheat variation;
- transfer ladle temperature stratification;
- mold flux incompatibility;
- casting speed fluctuation;
- excessive secondary cooling.

Different process metallurgy control strategies are required for the production of high quality microalloyed steels with low residual elemental levels since the kinetics and thermodynamics for the removal of these detrimental residuals are different and can sometimes conflict with their intended purpose. Although BOF and EAF steelmaking furnaces, secondary steelmaking facilities and continuous casters are often considered similar around the world, there are often inherent differences in operational practices. Similar equipment and processing of similar steel grades can result in varying degrees of slab, billet and bloom surface quality and performance. Consequently, each operation should thoroughly understand those specific unique process metallurgy variables that have a direct influence on surface quality, and then, develop practices accordingly to suit their steel grade family of microalloy compositions and customer requirements.

5.2 Pinholes/Porosity Root Cause/Mitigation Solutions

If gases are not properly controlled porosity/pinholes can form on the slab/billet surface. When the sum of these gases at 90% solidification $Argon+H_2+N_2+CO+CO_2 > 1\ atm$ pinholes/porosity can form on the slab/billet surface.(5) Therefore, it is not difficult to see why surface and subsurface pinholes/porosity can form. Pinholes/porosity can be 1-3 mm in diameter and be located subsurface as deep as 10 mm below the surface. They can be located on both the narrow and broadface of the slabs on both top and bottom corners and also in the broadface body. From experience, this has been the number one issue on many plate/coil related surface defect issues. Mitigation to control pinholes/porosity formation is as follows:

- keep nitrogen as low as possible, preferably < 70 ppm;
- total argon flow around the caster at ALL locations should be kept to < 10 l/minute total flow;
- keep hydrogen levels as low as possible. Typical hydrogen values in non-vacuumed degassed steels are in the 4-8 ppm range. Vacuum degassing keeps the hydrogen in 1-4 ppm range depending on degassing cycle time;
- target total oxygen < 20 ppm;

- lower carbon content. Lower carbon results in less CO/CO_2 formation. Pinholes/porosity issues tends to be higher in carbon contents >0.10% vs. those with low carbon such as pipeline steels ≤0.07%. Not only will slab/plate/coil surface quality improve with lower carbons, but there are other significant to developing lower carbon grades such as improved weldability, improved elongation/forming, and improved toughness.

The critical success factor here is to lower the total gas content in the liquid steel to minimize formation of pinholes/porosity. Operational metallurgy adopting the Niobium- Low Carbon Low Alloy (Nb-LCLA) approach to minimize this defect by moving to lower carbon contents is currently being successfully utilized. It is not expected that every pinhole/porosity will be eliminated, but the goal is to minimize the size and frequency to create the desired finished surface quality of the slab, plate and coil.

5.3 Cracks - Longitudinal Root Cause/Mitigation Solutions

Longitudinal crack formation is all about heat transfer characteristics between the mold and the liquid steel during casting. Key parameters that affect the formation of longitudinal cracks are as follows:

- poor mold level control - > ±5 mm;
- mold water inlet temperature > 35°C, Figure 9 shows the effect of water cooling efficiency vs. increasing water temperature with a steep drop in cooling efficiency in the 27°C-49°C range. This of course changes the heat transfer characteristics between the mold and steel significantly;
- casting speed > 1.3 m/min;
- too high of a superheat, >30°C, targeted superheat should be approximately 20°C average maximum for overall good quality;
- improper mold taper (edge longitudinal cracks);
- improper mold powder for carbon content, casting speed and mold water inlet temperature: (i) Basic carbon ranges: low carbon <0.09%, medium carbon 0.09%-0.15% (peritectic), range varies up or down slightly depending on manganese content, high carbon >0.15%; and (ii) Choosing the correct mold powder for the casting speed and carbon contents is critical to controlling these longitudinal cracks. Multiple mold powders may be needed to cover the three basic carbon ranges along with various casting speeds and mold inlet water temperature. Trying to operate with one mold powder to cover all carbon contents and possible casting speeds/mold water temperature is a common mistake;
- wet or damp mold powder changes the heat transfer characteristics of the mold powder that can also contribute to longitudinal cracks.

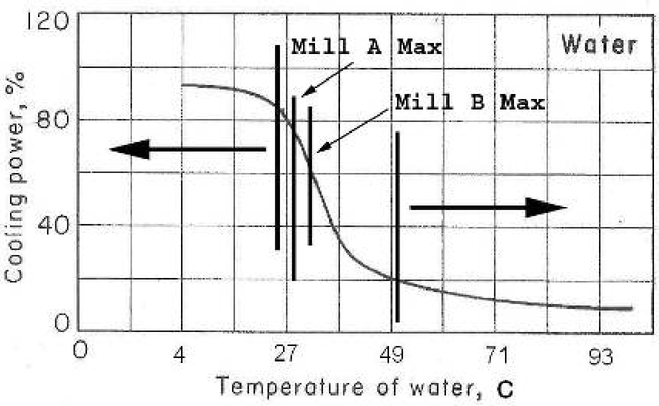


Figure 9. Cooling efficiency of water vs. temperature affecting heat transfer characteristics during casting. Note control limits examples of two different mills.

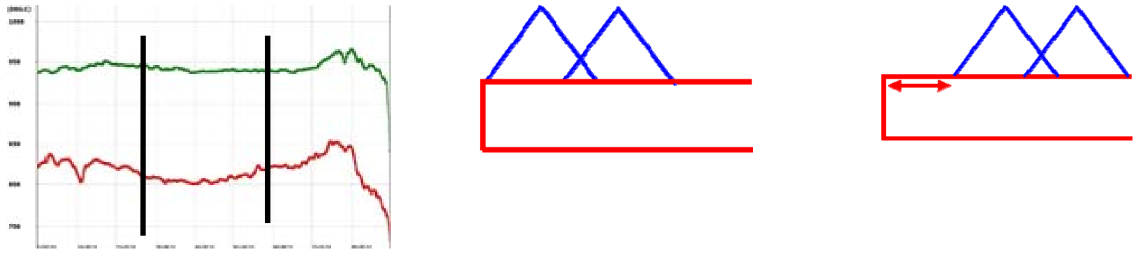
Proper control of one or several of the key parameters listed above results in the desired result of minimization or total elimination of longitudinal cracking issues. Current operational metallurgy is adopting the Niobium- Low Carbon Low Alloy (Nb-LCLA) approach to eliminate this defect utilizing lower carbon contents and moving out of the peritectic carbon (0.09%-015%) casting region.

5.4 Cracks – Transverse Root Cause/Mitigation Solutions

Transverse cracks are strictly a ductility issue of the steel during bending and unbending zones of the caster. The steel needs to have sufficient ductility to be able to bend below the mold and unbend at the runout of the caster. The only exception to this is a true vertical caster where there is only an unbending zone. Main factors that affect the ductility of the steel during casting are as follows:

- strain rate;
- non-uniform temperature slab body to slab corners;
- precipitate formation (size/frequency) – vanadium, niobium, titanium, aluminum, carbon, boron, nitrogen;
- inclusions – sulfides, oxides;
- grain size/microstructure formation.

When the ductility is affected by one or multiple parameters listed above and the steel is put into tension at the caster, crack formation may occur in either the bending zone below the mold or the unbending zone further down the length of the caster. It has been well documented over the years that there are temperature zones of low ductility due to the various factors shown above during the casting process. This temperature zone is typically in the 700°C-900°C range depending on the factors or combinations of factors involved. It is in this range where the ductility may be low enough such that when the slab is put into tension or there are other potential stress risers present such as deep oscillation marks. However, in many cases only some slight modification to one or several factors are sufficient to raise the ductility a few percentage points to successfully cast without cracking. Poor superheat control and temperature variation is often the root cause for cracking in higher carbon equivalent steels with deep hot ductility troughs. Figure 10(6) shows the temperature variation between the top corner of the slab in the unbending zone vs. that of the body. Note that the corner is below 900°C and the body is above 900°C which puts the corner into a potential lower ductility temperature zone. Also can be seen an effect of reducing the casting speed 0.1 m/min (between black lines) on the top slab corner temperature vs. very little influence on the body temperature. Figure 10 also gives illustration on how to control the secondary water cooling in the spray chamber to regulate the slab temperature across the width of the slab.



Slab body temperature (green line) vs. slab top corner temperature (red line) in the unbending zone.

Spray to edge if goal is to maintain cold corners

Spray off-corner if goal is to maintain hot corners

Overlap ~30-45 mm to avoid reheating

Figure 10. Example of various edge/body secondary spray cooling patterns to control slab temperatures properly for improved ductility.

A summary of key parameters that affect the formation of transverse slab cracks are as follows:

- bending or unbending in a critical temperature range of low ductility, 700°C-900°C. Again only a slight improvement in ductility is typically needed to result in successful casting;
- casting machine misalignment >0.5 mm;
- improper roll gap settings ≥± 0.5 mm;
- thermocycling from improper water distribution;
- non-uniform temperature distribution from plugged sprays;
- carbon, nitrogen, sulfur content too high: carbon > 0.12%, nitrogen > 70 ppm, sulfur > 0.010%;
- niobium, vanadium, aluminum, titanium, boron precipitate formation size, distribution and frequency too large;
- deep oscillation marks > 1 mm depth;
- excessive narrow face taper > 1.2%/m;
- poor mold level control >± 5 mm;
- improper mold powder chemistry design;
- too high of a superheat, >30°C, targeted superheat should be approximately 20°C average maximum for overall good quality.

Proper control of anyone or combination of the key parameters can result in successful casting of slabs free of any transverse cracks. Current operational metallurgy is adopting the Niobium- Low Carbon Low Alloy (Nb-LCLA) approach to eliminate this defect by reducing the formation/frequency/distribution of carbide formation.

5.5 Star Cracks/Oscillation Marks Root Cause/Mitigation Solutions

Star crack is a problem that has for the most part been decreased with proper alloy designs in the molds. It is not a typical problem for today's casters.

The proper oscillation stroke, frequency and heat transfer must be properly employed for each caster to assure that oscillation marks do not become stress risers for crack initiation. Generally, oscillation marks < 1mm in depth do not cause any adverse slab/plate/coil surface quality issues. Examples of acceptable oscillation marks where given in previous Figure 8.

5.6 Poor Scarfing Root Cause/Mitigation Solutions

Generally, if proper technique is used, then rolled surfaces will be free of defects associated with this operation. A good practice to assure a smooth transition is that the scarfing pass width should be 6x the scarfing depth (feathered technique). Examples of proper scarfing techniques can be seen in Figure 11.

Example of good scarfing technique with proper scarfing depth to width ratio (feathered technique).

Example of good scarfing showing flat transition near the slab edge. Note the overall smoothness across the scarfing.

Figure 11. Examples of proper scarfing techniques to avoid potential surface quality issues in rolled plate and coil.

In addition, for those grades with IIW/DO CE ≥ 0.50, slabs should be preheated to a temperature of 250°C minimum to avoid thermal shock of the surface during any scarfing operation. This temperature should also be applied for cutting and charging to the reheat furnace to avoid any catastrophic cracking of the slab. Some grades with CE’s approaching 0.50 may be able to use a slightly lower temperature, but in no circumstances in these grades should the temperature be less than 150°C.

5.7 Mechanical Mold Wall Contamination, Scratches, Gouges Root Cause/Mitigation Solutions

There can be mold wall contamination similar to what can cause star cracks that result in hot-shortness during heating/rolling. There can also be scratches and/or gouges, etc. that if deep enough will not oxidize off during reheating and result in a rolled in defect. These typically are not a major issue, but again care in handling slabs will minimize any scratches and/or gouges. Mold wall contamination is controlled in today’s casters through proper mold wall alloy designs.

6 CONCLUSIONS

A variety of slab related defects which contribute to surface quality issues, when properly identified, can be connected to the key operational factors/parameters that are the root cause. Proper controls of the casting process in terms of casting speed, oscillation stroke, superheat, residual chemistry and cooling rates can result in high quality slabs/billets for the production of plate, coil and long products regardless of the carbon equivalent. Microalloyed grades of steel including niobium can be successfully cast with the proper understanding and controls in place. High quality, niobium microalloyed chemistries are being successfully produced everyday around the globe. Tighter process control during the melting, casting and hot rolling and proper understanding and interpretation of the defects through the root cause analysis approach is the critical success factor to assure the high quality consistent production of not only niobium microalloyed steels, but all steel grades on every heat.

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