STEELMAKING AND CONTINUOUS CASTING PROCESS METALLURGY FACTORS INFLUENCING HOT DUCTILITY BEHAVIOR OF NIOBIUM BEARING STEELS

Steven G. JANSTO

CBMM – Reference Metals Company, Bridgeville, PA, USA, jansto@referencemetals.com

Abstract

Over 200 million tons of Nb-bearing steels were continuously cast and hot rolled globally in 2012. These Nb-bearing plate, bar and sheet products are manufactured throughout the world. Numerous publications discuss the traditional ductility trough for carbon steels with and without microalloy additions of Nb, V and/or Ti. The steelmaking and process metallurgy parameters under actual mill conditions are rarely correlated to the hot ductility behavior. The hot ductility troughs associated with simple carbon-manganese steels can also result in surface and internal quality issues if certain steelmaking and casting parameters are not followed. Although higher carbon equivalent steels generally exhibit inherently lower hot ductility behavior, as measured by percent reduction in area at elevated temperature, these steels still exhibit sufficient ductility to satisfactorily meet the unbending stress and strain gradients existing in the straightening section of most casters. The relationship between the steelmaking and caster operation and the resultant slab quality is related through the hot ductility behavior. This global Nb-bearing continuous casting steel research study concludes that the incidence of slab cracking during casting is related more to the steelmaking and caster process parameters. These parameters include the superheat variation, transfer ladle temperature stratification, mould flux incompatibility, casting speed fluctuation, elemental residual chemistry level and excessive secondary cooling. This paper defines these operational root causes supported by physical metallurgy hot ductility data from industrial samples.

Keywords: continuous casting, hot ductility, melting, niobium, process metallurgy, strain rate

1. INTRODUCTION

Continuous casting surface defects and internal defects impart a direct impact on the overall steel production operating costs, internal and external cost of quality and delivery performance. Some Nb, V and Ti high carbon equivalent, high strength microalloyed steel grades may be prone to continuous casting surface and crack defects depending upon specific metallurgical factors and given set of operational conditions at the steelmaking furnace, ladle metallurgy station and caster. In other situations, both internal and external surface quality is excellent for the same high carbon equivalent, high strength microalloyed steel grade. This study integrates both the process metallurgy and physical metallurgy to better understand the reasons for crack initiation in Nb-bearing grades and more importantly, the conditions and combination of parameters in action, when Nb-bearing steel billets, blooms and slabs are produced crack-free. There is a lack of published literature and research performed-to-date that directly connect the steelmaking-caster industrial operations with the resultant surface quality, hot ductility behavior and steelmaking/continuous casting conditions to cast crack-free microalloy-bearing steel products. Many researchers conclude that the root cause is simply the hot ductility trough for a given composition, yet not even incorporating or considering the effects of process parameters such as tap temperature, superheat, casting speed, oscillation frequency, soft reduction, mould flux and primary/secondary cooling in their research work. [1,2]

The inter-relationships of these process metallurgy parameters with the kinetic and thermodynamic conditions and resultant effect on the hot ductility behavior of various steel grades is rarely reported or published. Although more complex and difficult, it is necessary to thoroughly understand these inter-
relationships and effect on the quality of industrially produced slabs. The intent of this research is to study and report such inter-relationships. For example, the interaction and possible synergistic effects of the various micro-precipitates may favorably affect the hot ductility behavior of the cast steel strand through the straightening or unbending section of the caster. The quality of the steelmaking process has a direct influence on the caster performance and internal and external quality of the slab. For example, the depth of the equiaxed chill zone and sub-surface strain field through the transition zone affects the propensity for cracking and the inter- or trans-granular fracture mechanisms. Figure 1 schematically represents these interrelationships.

Fig. 1 Schematic Physical/Process Metallurgy Representation

2. DISCUSSION

2.1. Steelmaking Considerations

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 steelmaking furnaces, secondary steelmaking facilities and continuous casters are often considered similar around the world, there are inherent differences in caster design and operational practices. Similar equipment processing the identical microalloyed steel grade can experience varying degrees of slab, billet and bloom surface quality. Tapping and tundish temperatures and temperature variability, casting speeds, mould flux, primary and secondary cooling, mould oscillation frequency and stroke and negative strip times are different for the same chemistry grades at different mills, even within the same steel company. Each operation should thoroughly understand their unique process metallurgy variables that have a direct influence on surface and internal quality and hot ductility behavior. Only then, can practices be developed accordingly to suit their microalloyed steel grade family of compositions, residual levels and customer requirements.

The inherent differences between Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF) operation that contribute to poor external surface and internal quality are well documented and for the
most part understood, with exceptions such as transverse cracking cause and effect. Several fundamental process metallurgy, chemistry and raw material considerations are often overlooked when evaluating root causes for poor surface quality. Four high priority root causes which influence hot ductility behavior in steelmaking operations involve: 1) nitrogen levels and variations, 2) residual levels such as antimony, copper, lead and tin, etc. in the scrap, 3) tapping temperature instability and resultant superheat variation and 4) excessive secondary cooling. [3]

Figure 2 shows the relationship between increasing nitrogen levels and increasing the crack susceptibility index for aluminum killed steels, particularly in continuous cast slabs for automotive, pipeline and value-added structural applications. Low nitrogen levels can be attained by using low nitrogen raw materials and through the incorporation of operational practices that minimize nitrogen pickup during the steelmaking process and subsequent processing, such as secondary ladle refining, steel transfer and casting from the tundish to the mould.

![Fig. 2 Effect of nitrogen on cracking index – aluminum killed steel](image)

It is preferred, of course, to operate the BOF below 50ppm N, thereby resulting in a consistent very low transverse crack index of 0.2. However, many BOF operations fall within the 50 to 65ppm band which falls on the steep section of the curve (0.2 to 0.6 transverse crack index dependent on N). Considerable variation in surface quality results on a day-to-day basis and hence, very unpredictable quality performance. From an operational and cost perspective, it is most effective to function on the horizontal zone of the quality vs. process control parametric function curve.

### 2.2. Minimization of Nitrogen Effect

After tapping into the secondary ladle metallurgy operation, the following practices may affect nitrogen levels and hence, hot ductility behavior at the caster:

1) Stirring practices must be consistent and vigorous stirring in the ladle furnace must always be avoided. The greater part of N pickup occurs from the exposure of the liquid steel surface to the atmosphere following break-up of the top slag layer to the atmosphere.

2) An argon shroud system can be used instead of nitrogen. A cost benefit analysis shows that the improvement in surface quality and reduction in defects within the cast product more than justifies the higher cost argon gas.
3) Avoid teeming ladle temperature stratification due to short argon stir treatment times, extended treatment times with intermittent stir cycles and long time periods between ladle transfer stations.

2.3. Superheat Considerations

A direct correlation exists between the absolute value of the superheat and the variability of the superheat differential during the continuous casting process. These variations become especially important during the continuous casting of microalloyed steels and directly influence the hot ductility behavior. Casting operations must develop superheat temperature practices for low, medium and high carbon equivalent steels (with superheat not exceeding a maximum 20°C to 25°C (depending on C-content and strain rate). Also, control of the temperature during casting through minimal superheat temperature variation between ± 2 to 4°C during the continuous casting process improves surface quality and hot ductility behavior.

2.4. Primary and Secondary Cooling Considerations at Caster

The primary and secondary cooling should be balanced at the minimum flow rates to safely operate and still maintain that the optimal equiaxed chill zone throughout the solidification shell over the entire length of the continuous cast strand. Optimization of the chill zone improves the hot ductility behavior of the slab as it moves through the unbending operation. These process metallurgy variables become even more critical as unbending temperatures decrease below the optimum 850-900°C range. Successful crack-free unbending is experienced as low as 750°C when controlling the superheat, nitrogen, carbon content, sulfur levels and primary/secondary cooling flow rates. Corner cracks may be eliminated through the practice of not applying water to the corner sections of the slab. [5]

3. RESULTS

3.1. Hot Ductility at Temperature

Hot ductility tensile tests are being performed on industrial samples procured from steel mills throughout the world including mills from China, Brazil, North America and Europe. Hot tensile test specimens were heated to the soaking temperature of 1300°C, held for 5 minutes and cooled to the desired test temperature per the cooling rate schedule of 60°C/minute to the given test temperatures of 700°C, 800°C, 850°C, and 900°C. Figure 3 illustrates the heating/cooling schedule for the 800°C test temperature.

![Fig. 3 Heating and cooling schedule example for 800°C test at two strain rates](image)

The sample family includes microalloyed (Nb, V and/or Ti) low carbon grades, peritectic grades and medium carbon grades. The selected range of steel chemistries represents grades some steel producers have
observed occasional surface related defects and transverse cracking. Several of the industrial samples provided for this research include steelmaking and caster machine operational and design parameters. The hot ductility strain rates employed on these industrial samples obtained directly off the caster are intended to simulate the actual strains encountered through the straightening section of the industrial casters. Industrial caster strain rates are typically 0.001/sec to 0.0001/sec through the straightening section of the caster.

Figures 4 and 5 present the percent reduction in area (%RA) versus hot ductility test temperature for a Nb bearing peritectic grade and a Nb-bearing low carbon (0.07%C) LCLA grade.

The improvement in the hot ductility behavior, measured as % reduction in area, is nearly double between the peritectic and the LCLA grades (i.e. 21% versus 45% at 800°C). The mechanical hot ductility behavior is more related to the carbon content than the presence of Nb in the solidification microstructure. The fundamental characteristics of this hot ductility behavior at higher carbon peritectic content necessitate tighter process control of both the absolute superheat and the superheat variation during casting independent of the microalloy composition. Figure 6 and 7 compare the hot ductility behavior of higher Nb concentrations (0.05 and 0.10%Nb) at low carbon levels (0.07% and 0.04%C).
For all four steels, the minimum %RA occurs at approximately 800°C. These hot ductility values are based upon laboratory hot ductility tensile tests. The importance of the presentation of this hot ductility data from industrial samples is that none of these slabs exhibited transverse or corner cracks. An analysis of the superheat control suggests the root cause for this excellent surface quality is temperature control. This body of work has established that a %RA as low as 20% results in the production of crack-free slabs. Published literature reported a minimum 40%RA is required to ensure crack-free casting of microalloyed steels. [2, 6] This published %RA data is nearly double the required %RA as measured by the hot ductility tensile test and overstates the ductility issues involved with the castability of Nb-microalloyed steels.

3.2. Superheat and casting speed effect on hot ductility behavior

Figures 4-7 show that with increasing strain rate, which means increased casting speed for a specific caster, the hot ductility behavior improves (i.e. higher %RA at temperature) for all Nb chemistries tested. There is also a relationship between increased casting speed and reduced superheat variation. Table 1 below presents a summary of the process metallurgy, recommended superheat control and casting speed based on this study.

Table 1. Hot ductility, superheat and casting speed relationship

<table>
<thead>
<tr>
<th>Strain Rate</th>
<th>Min %RA at 800°C</th>
<th>Superheat  °C- Control</th>
<th>Casting Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCLA- Low Nb</td>
<td>0.001</td>
<td>60</td>
<td>20-25</td>
</tr>
<tr>
<td></td>
<td>0.0001</td>
<td>45</td>
<td>20-25</td>
</tr>
<tr>
<td>Peritectic-Low Nb</td>
<td>0.001</td>
<td>32</td>
<td>17-23</td>
</tr>
<tr>
<td></td>
<td>0.0001</td>
<td>20</td>
<td>17-23</td>
</tr>
<tr>
<td>LCLA-Medium Nb</td>
<td>0.001</td>
<td>50</td>
<td>20-25</td>
</tr>
<tr>
<td></td>
<td>0.0001</td>
<td>32</td>
<td>20-25</td>
</tr>
<tr>
<td>Very Low C-High Nb</td>
<td>0.001</td>
<td>31</td>
<td>20-25</td>
</tr>
<tr>
<td></td>
<td>0.0001</td>
<td>20</td>
<td>15-20</td>
</tr>
</tbody>
</table>

The methodology suggests that superheat control per Table 1 should be the first priority for improved surface and sub-surface quality. With proper superheat control, the opportunity to increase casting speed by 5 to 10% offers immense opportunities to further improve the solidified equiaxed chill zone depth, hot ductility behavior at higher strain rates and improved steel slab mechanical property integrity as well as productivity.

4. CONCLUSIONS

Global experience has demonstrated quality reliability through the production of over 200 million tonnes of high quality Nb-bearing steels. The control of the nitrogen, carbon, sulfur and residual chemistry levels, superheat variations and water cooling influence the hot ductility behavior. This study has established hot ductility characterization curves for industrial produced steel samples from continuous cast slabs (i.e. not laboratory heats). These Nb-bearing carbon grades, from 0.04% to 0.16%C, exhibited no
transverse or corner cracks. The minimum %RA versus temperature relationship has been defined to achieve crack-free slabs. Through the operational process metallurgy control of the two primary drivers, superheat control and secondary cooling, the %RA required for crack-free casting is decreased to as low as 20% The total superheat should be controlled to less than 15°C to 25°C dependent upon the strain rate, carbon and nitrogen levels for microalloyed steel heats with a process metallurgy aim of ±2 to 4°C temperature variation throughout the casting of the heat. Such superheat control is well established and within current operational melt shop and continuous caster practice capability.

LITERATURE


