STEELMAKING AND CONTINUOUS CASTING PROCESS PARAMETERS AND PHYSICAL METALLURGY RELATIONSHIPS AFFECTING HOT DUCTILITY BEHAVIOR OF NIOBIUM-BEARING STEELS[1]

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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. The melting and casting practices to assure production of crack-free slabs, billets and blooms of high surface quality is presented. Much has been published about the traditional ductility trough associated with higher carbon equivalent steels with and without microalloy additions of Nb, V and/or Ti. However, the steelmaking and process metallurgy parameters 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 high carbon equivalent steels 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 to the steelmaking and caster process parameters. These parameters include the elemental residual chemistry level, superheat variation, transfer ladle temperature stratification, mould flux incompatibility, casting speed fluctuation, and excessive secondary cooling. This paper defines these operational root causes supported by physical metallurgy hot ductility data.

Key words: Continuous casting; Hot ductility; Niobium; Steelmaking.

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1 INTRODUCTION

Continuous casting surface defects and internal defects impart a direct impact on reducing the overall steel production operating costs, internal and external cost of quality and delivery performance. As known, 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 caster. In other situations, both internal and external surface quality is excellent. This study integrates the process metallurgy and physical metallurgy to better understand the reasons for cracks 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 surface quality performance and steelmaking/continuous casting conditions to cast crack-free microalloy-bearing steel products.

The inter-relationships between the process metallurgy parameters, the resultant kinetic and thermodynamic conditions and its effect on the hot ductility behavior of various steel grades is rarely reported or published. 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.

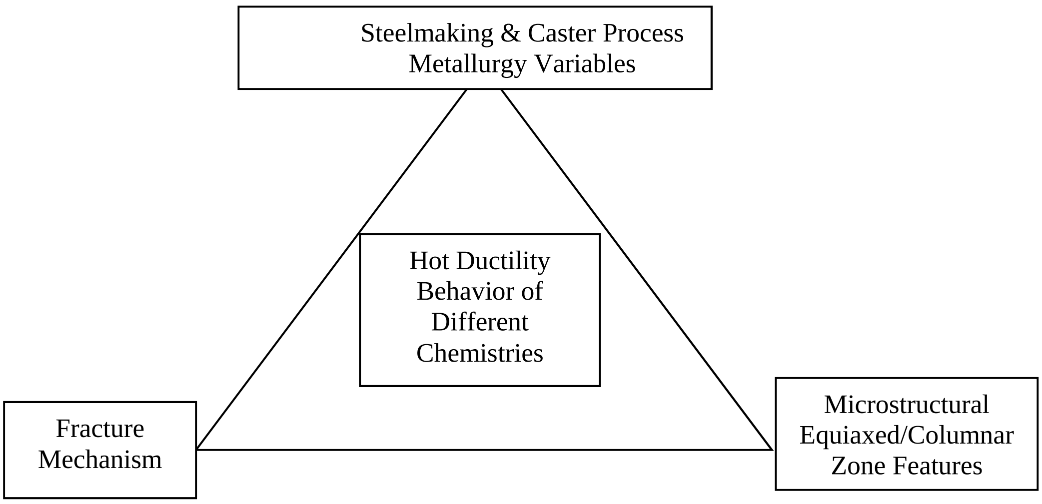

Figure 1. Schematic physical/process metallurgy representation.

1.1 Background Information

Based upon comparisons of steelmaking and operational practices at different steel mills around the world, experience indicates numerous mills consistently produce defect-free Nb-bearing slabs, billets and/or beams, while a few other mills encounter difficulties. Generally, those 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, and typically are unsuccessful resolving the quality issue. Much research data has been published regarding the ductility trough for simple carbon-manganese steels as well as microalloyed steels which is an inherent property of various chemistry steels.[1-3] Yet, identical Nb-bearing chemistries are successfully produced everyday around the globe. Often, the cracking during casting is the result of steelmaking and caster practice related to the residual chemistry superheat variation, transfer ladle temperature stratification, mould flux incompatibility, casting speed fluctuation, and/or excessive secondary cooling. This paper will explore some of these root causes, which when corrected, minimize and/or eliminate cracking and improve overall surface and internal quality across the entire product mix.

2 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 design and operational practices. Similar equipment processing the identical steel grade can experience varying degrees of slab, billet and bloom surface quality. Tapping and tundish temperatures and 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 specific 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.

2.1 BOF and EAF Operations

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.[4]

Figure 2 shows the relationship between increasing nitrogen levels and increasing the crack susceptibility 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.

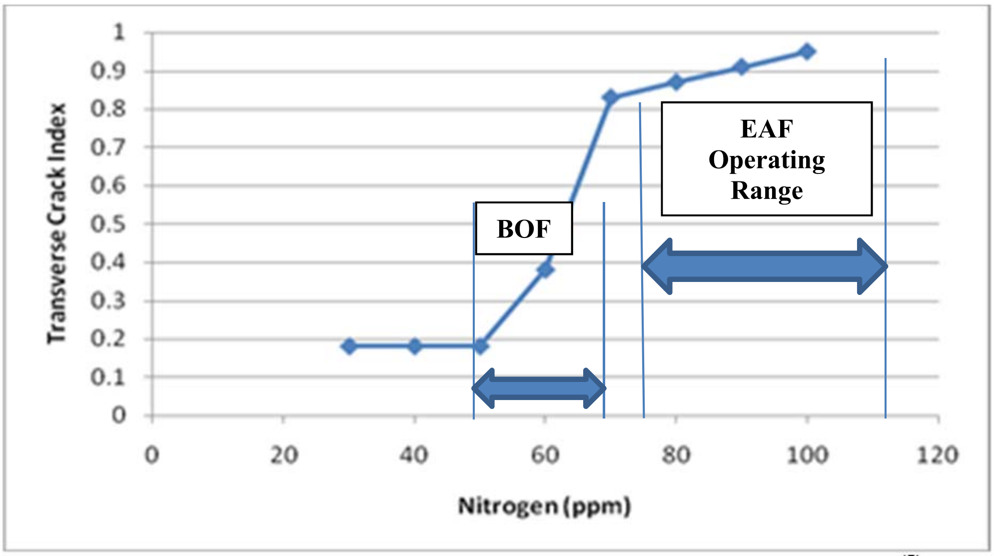

Figure 2. Effect of nitrogen on cracking index – aluminum killed steel.[(5)]

It is preferred, of course, to operate the BOF below 50ppm N, thereby resulting in a consistent transverse crack index of 0.2. However, many BOF operations fall within the 50ppm to 65ppm band which falls on the steep section of the curve (0.6 to 0.2 transverse crack index dependent on N) which results in 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. Current BOF practices to obtain consistent N levels operate at less than 50ppm to 60ppm for integrated steelmaking includes:

1) Maintain hot metal titanium content above 0.10% since the higher the titanium in the liquid iron from the blast furnace then the lower the nitrogen content in the hot metal.
2) Avoid re-blows at the BOF. The N content increases steeply with increased re-blowing at the lower carbon levels (less than 0.15%C). There is excessive nitrogen pick-up if the re-blow time exceeds 60 seconds.
3) A reduction in the tap temperature is advantageous with a commensurate reduction in N. The variation or scatter in the steel N levels is also reduced at lower tap temperatures.
4) Incorporation of a partial deoxidation practice with the usage of limestone chips during tapping which reduces nitrogen pickup during tapping by as much as 10ppm.
5) Maintain excellent tapping practices to minimize BOF slag carry-over.[6] The majority of EAFs that produce Nb-microalloyed steels generally tap between 65 to 90ppm. Lower nitrogen levels approaching BOF steels may be achieved through vacuum degassing; however, this operation adds significantly to the operational cost per tonne. In order to obtain consistent N levels closer to 65ppm, some of the following EAF practices are implemented:

1) Selective segregation of microalloyed scrap from C-Mn scrap minimizes residuals (i.e. Cu, Pb, Sb, Sn, etc.) which can deepen and widen the hot ductility trough.
2) The introduction of 15 to 25% direct reduced iron into the scrap charge to improve steel cleanliness.
3) Addition of hot metal, cold pig iron, decarburized granular iron and/or iron carbide has been added to high quality microalloyed steel grades to dilute the residual elements from the scrap.
4) The effects of sulphur and high nitrogen levels should be closely evaluated, again, as a result of the deepening and widening of the hot ductility trough. Calcium shape control exhibits a positive effect on hot ductility performance. In some cases, for a similar grade, EAF produced steel may require calcium shape control to offset higher residual contents. In contrast, some BOF produced steels may not require calcium shape control.(6)

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 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 treatment times, extended treatment times and long time periods between ladle transfer stations.
4) Develop superheat temperature practices for low, medium and high carbon equivalent steels (with superheat not exceeding 20°C) and minimal superheat variation during casting (±2-4°C).

3 CASTER OPERATIONAL CONSIDERATIONS

There are several connecting variables in an industrial caster between the tapping of the molten steel from the transfer ladle to the tundish that may significantly affect the depth of the equiaxed chill zone. The location width of the transition zone, defined as the Equiaxed-Columnar-Grain (EACLG) transition zone from equiaxed grains to the initiation of the columnar grains influences the overall hot ductility behavior. These connecting variables include transfer pour time and steel temperature, superheat temperature, reoxidation conditions and mould flux practices. These are rarely discussed in relation to their effects on hot ductility. These variables are typically not part of a research or laboratory study due to the difficulty encountered in simulating the actual casting process.

The solidification of the molten steel into a solid semi-finished bloom involves the removal of superheat. Superheat is defined as the heat contained by the steel in excess of the heat content at solidification or liquidus temperature (i.e. excess temperature with respect to the liquidus temperature). The absolute value and variation during teeming has a direct correlation to the degree of micro and macrosegregation as well as surface quality. In the laboratory, it is quite difficult to simulate these operational variables when conducting Gleeble hot ductility tensile tests. Based upon the results of actual casting operations at a mill producing low carbon Nb-bearing steel, the area percent of the equiaxed zone in the cross-section of the cast slab is found to decrease with an increase in superheat temperature. Figure 3 below illustrates the transition zone from the equiaxed zone to the columnar dendritic zone.

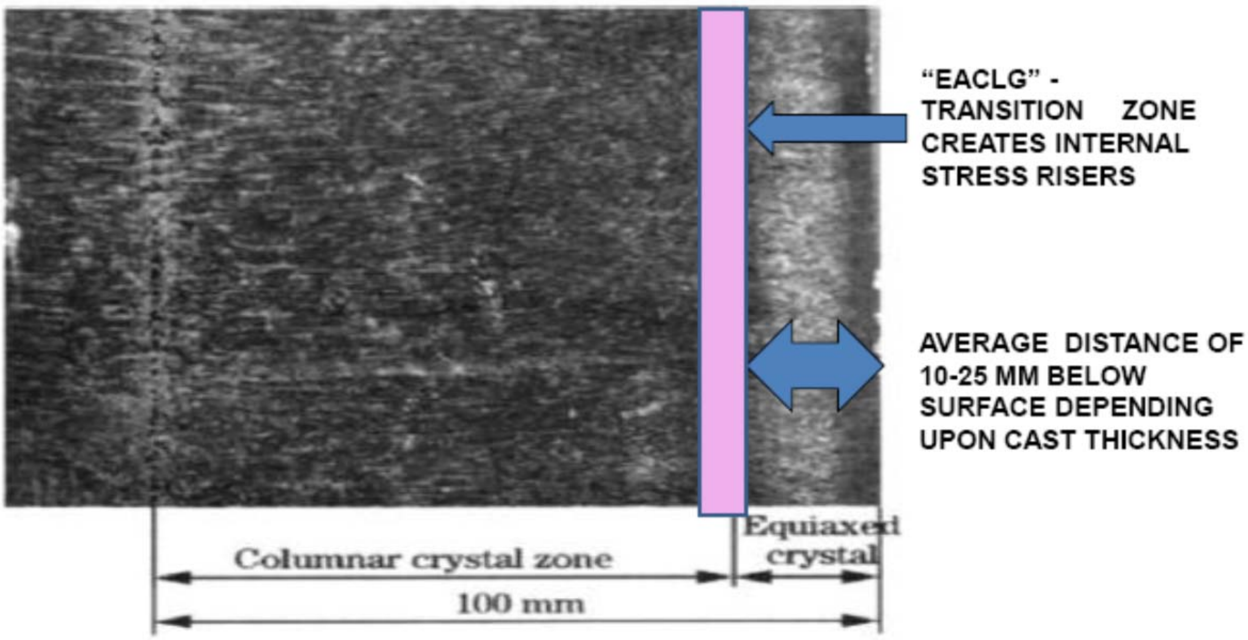

Figure 3. Equiaxed and columnar zone macrograph.

Micrographic examination of different continuously cast slab samples reveals a significant difference between the equiaxed crystal chill zone depth, columnar dendritic zone and the caster operational parameters. The transition zone from the equiaxed to columnar zone results in a mixed grain can vary between 25 to 100 mm below the equiaxed chill zone. As result of the mixed grain zone, stress risers are created below the surface at this point and can act as crack initiation points during the unbending of the slab through the straightening section of the caster between 700 and 950°C. The primary zone cooling greatly influences the initial solidification front and chill zone thickness and then, the secondary cooling affects the resultant behavior through the straightening section of the caster.[7]

3.1 Centerline Segregation

Simultaneously, the degree of centerline segregation will also decrease with increased equiaxed zones. Usually, a transition of the segregation pattern from U-segregation to V- segregation occurs between 20 to 25°C superheat. The size of the V-segregation increases gradually with increasing equiaxed zone. The maximum degree of segregation or peak is considered to be an index of quality of the cast billet and related to the superheat of liquid steel during casting. Two of the most effective measures to eliminate cracking are temperature control of the liquid steel for casting and reduction of the cooling rate in the secondary cooling section of the caster. The demands for high quality steel place severe restrictions on the temperature of the liquid steel supplied to the continuous caster.[8] For example, if the steel superheat is too high, then the centerline segregation will be adversely affected and there will be a greater probability of breakouts. If the superheat is too low, there can be problems of nozzle blocking and freezing in the tundish and the heat of steel may have to be poured back into the BOF. Therefore, a compromise must be met between conditions that give good castability and yield which simultaneously allow solidification to develop resulting in good internal and surface quality. Continuous casting demands that the molten steel is supplied at a temperature that is maintained within set limits for the duration of the cast which directly affects the chill zone thickness and the depth of the equiaxed to columnar transition zone location.

4 HOT DUCTILITY TEST RESULTS AND DISCUSSION

Hot ductility tests are being performed on industrial samples procured from steel mills throughout the world including mills from China, Brazil, North America and Europe. 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 expressed occasional surface related defects and transverse cracking. In several of the investigated cases for this research, steelmaking, caster machine and rolling parameters have been furnished from the steel companies who provided samples such that the ductility test conditions will simulate the actual caster conditions.

4.1 Percent Reduction of Area versus Straightening Temperature Range Results

All steel samples were industrial samples and no laboratory heats. Laboratory heats have been inaccurate in many cases simulating the hot ductility phenomena and process metallurgy variable that dramatically affect behavior through the straightening section resulting in invalid conclusions. All hot tensile tests were performed on a Gleeble 3500 model. The industrial steel samples were heated to 1300°C to assure the microalloy precipitates went back into solution. Samples were cooled at 60°K/second rate (simulating the cooling rate on the industrial caster) down to the test temperature. Test temperatures were between 700 to 900°C to simulate straightening (unbending) temperatures at the industrial casters. Strain rates simulated the actual operational strain rate at the caster (i.e. between 0.001 and 0.0001 mm/mm/second). A collection of hot ductility curves for Nb-microalloyed low carbon and peritectic carbon grades for low, medium and high Nb levels is illustrated in the following Figures 4 through 7.

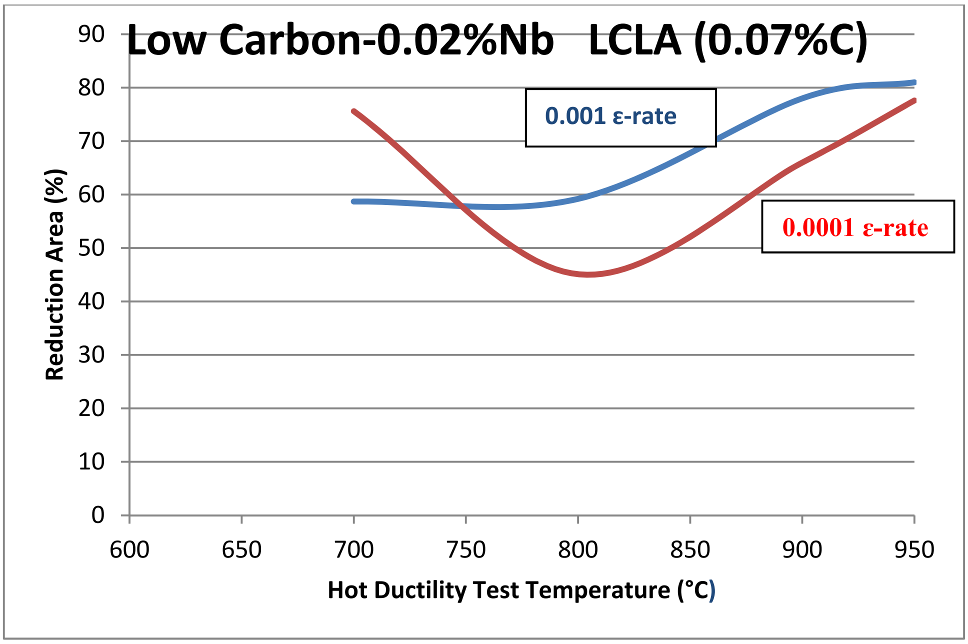

Figure 4. Low Carbon Low Alloy (LCLA) hot ductility behavior.

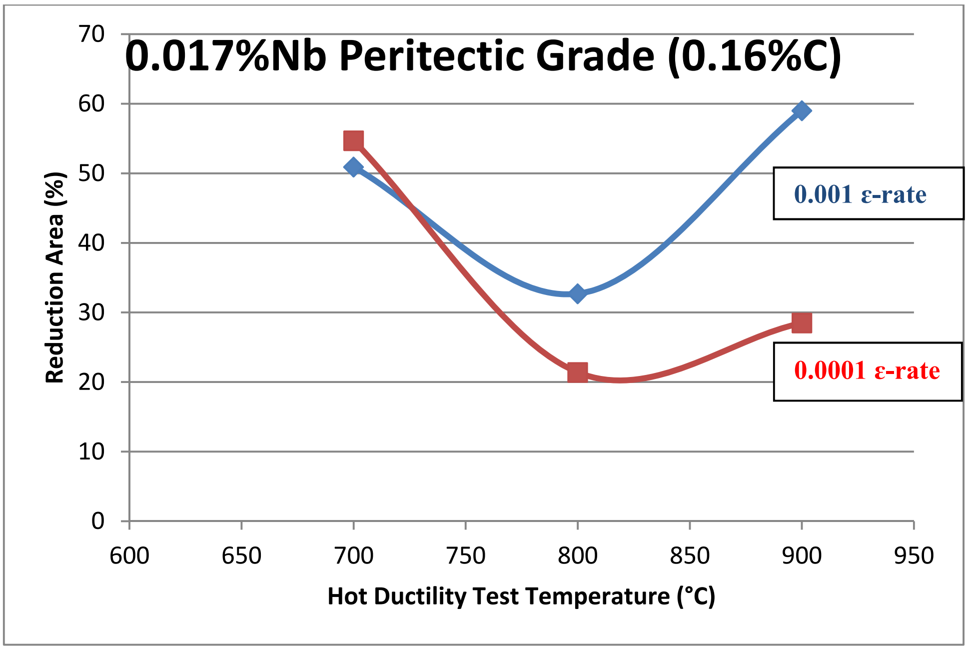

Figure 5. Peritectic hot ductility behavior.

The significant improvement in hot ductility behavior by a reduction in carbon from 0.16% to 0.07% at 0.02%Nb is nearly double from 20%RA at 800°C for the peritectic grade to 42%RA at 800°C for the Nb-LCLA (0.07%C) at the low strain rate of 0.0001/second. This metallurgical strategy has significantly improved slab surface quality and has been applied to light, medium and heavy section beams as well as windtower supports.

Current development involves application to heavy machinery. A further reduction in carbon for high Nb (0.08%Nb) HTP pipeline steels results in the hot ductility behavior shown below in Figure 6. At slow casting speed, much tighter superheat control is necessary in the range of 15 to 20°C. It is more prudent to increase the casting speed approaching the 0.001 strain rate if possible which allows for slightly higher acceptable variability in superheat.

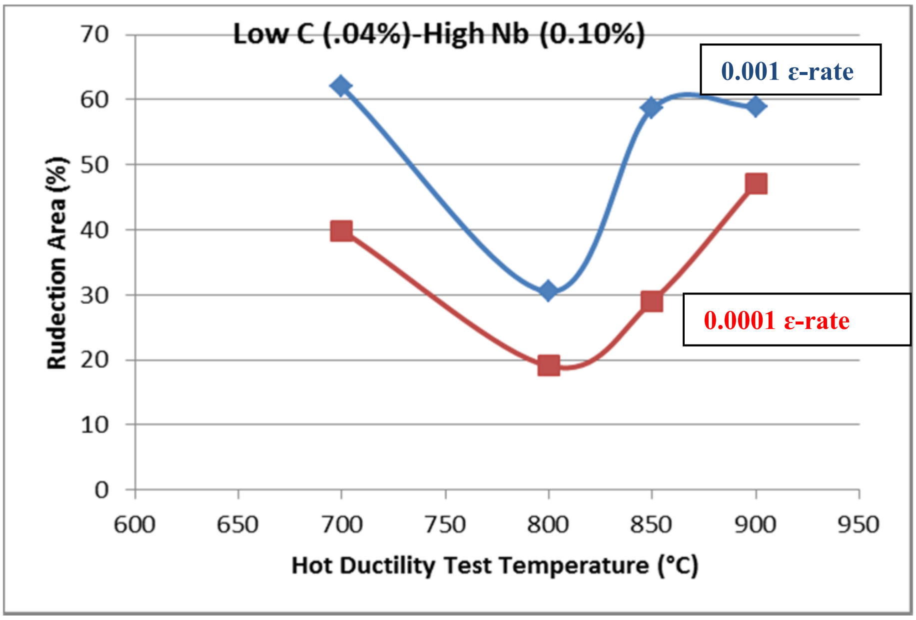

Figure 6. Low carbon high Nb hot ductility.

Superheat control of 15 to 20°C will ensure crack-free casting of the lower carbon high Nb grades based upon industrial trials and operational experience. The 20% reduction in area for the 0.0001 strain rate through the unbending section is acceptable for superior surface quality.

At the medium Nb level of 0.05% and low carbon at 0.07%C, superheat control becomes more restrictive than the LCLA, however, ductility behavior is still high above the reduction in area necessary to assure for crack-free casting of these Nb-bearing slabs as shown in Figure 7.

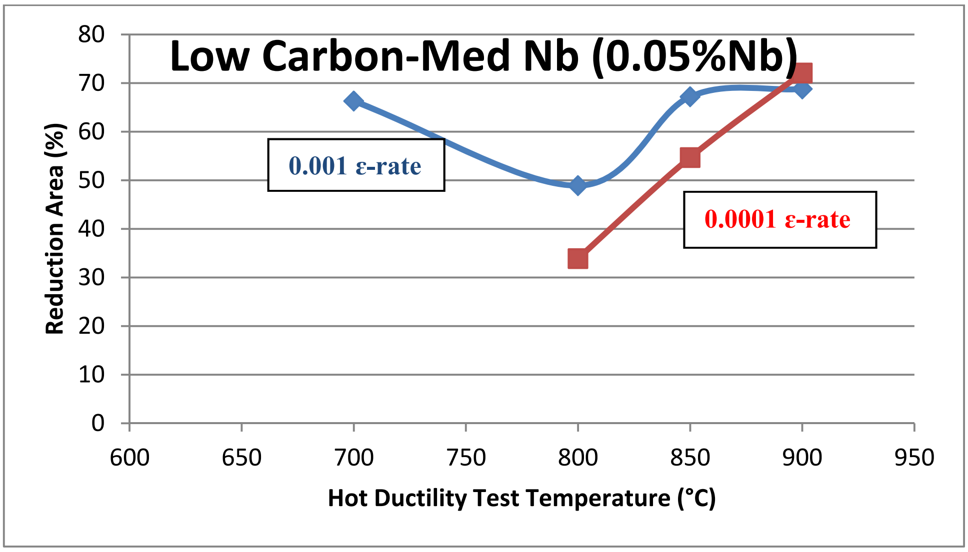

Figure 7. Low carbon medium Nb hot ductility.

4.2 Superheat and casting speed effect on hot ductility behavior

The influence of the absolute value of the superheat and the variability of the superheat during the sequence of the cast directly affects the frequency of transverse cracking during unbending in the caster. Also, it has been shown in Figures 4-7 that with increasing strain rate, which means increased casting speed, the hot ductility behavior improves for all Nb chemistries tested. Of course, there is a close connection between increased casting speed and reduced variation in superheat variation. Table 1 below presents a summary of the process metallurgy recommended superheat control and casting speed based upon the test data from this study to further improve surface quality and minimize/eliminate the incidence of transverse crack propagation through the unbending section of the caster.

Table 1. Hot ductility, superheat and casting speed relationship

	Strain Rate	**Min %RA at 800°C**	**Superheat °C- Control***	**Casting Speed**
LCLA- Low Nb	0.001	60	20-**25**	OK
	0.0001	45	**20**-25	OK
Peritectic-Low Nb	0.001	32	17-23	Increase
	0.0001	20	17-23	Increase
LCLA-Medium Nb	0.001	50	20-**25**	OK
	0.0001	32	**20**-25	Increase
Very Low C-High Nb	0.001	31	20-25	OK
	0.0001	20	15-20	OK

** The superheat control recommendations in Table 1 are based upon sulphur levels less than .005%. At higher sulfur levels the superheat control range is reduced by approximately 5°C. Superheat control essential.*

4.3 Soft Reduction Capabilities and Quality Effect

Casters which are designed with soft reduction capability and proper operational control will produce cast strands of higher quality than those casters lacking soft reduction. Soft reduction is quite advantageous for improving the quality of Nb-bearing slabs, billets and beam blanks. Soft reduction consists of the application of a slight reduction to the strand in the area where the liquid cone-like core is closing. The purpose of this soft reduction is to close the porosity voids created from the completion of the solidification of the strand. This reduction proves advantageous in addressing several of the residual element issues previously discussed in this paper. The soft reduction breaks up the interdendritic bridges formed during solidification and minimizes macrosegregation. Again, the optimal process parameters for each mill will vary depending upon caster design, composition of steel grades, and steel temperature practices. Universally, the key parameters of importance are: 1) casting speed, 2) the percentage reduction applied at each soft reduction point and 3) the total percentage reduction applied.

4.4 Secondary Cooling Considerations

The faster the cooling rate close to the surface of the slab (~200°C/minute) the greater the chance that precipitates are refined leading to reduced ductility (Figure 8).

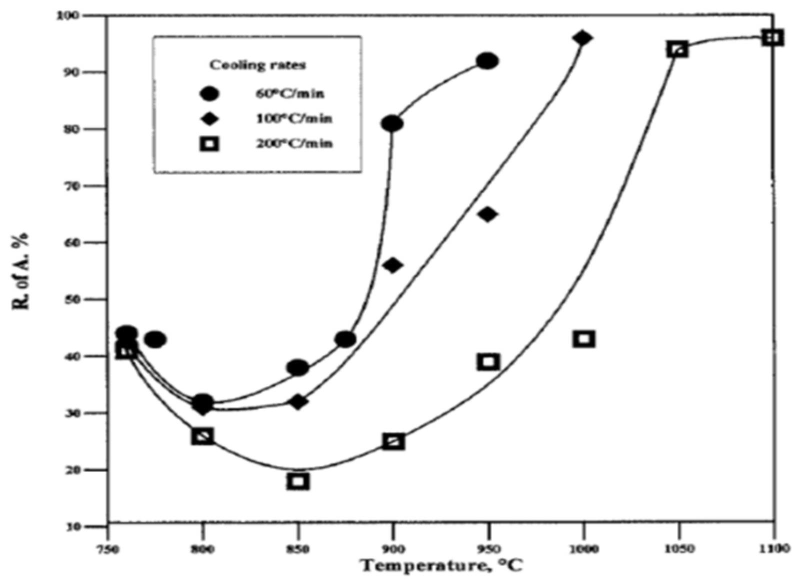

Figure 8. Hot ductility curves for as-cast C-Mn-Nb-Al steel at different cooling rates.[9]

Figure 8 illustrates the significant improvement in hot ductility at the recommended operating window for straightening (unbending) between 850° and 900°C. Note at 850°C when the cooling rate in the secondary cooling section is reduced by 50% from 200°C/min to 100°C/min, the reduction in area (RA) improves by 50% from 20 to 30% RA. At 900°C, the reduced cooling rate improves the hot ductility from 25 to 45%.

5 CONCLUSIONS

The casting speed, superheat control and primary/secondary cooling have a profound effect on the hot ductility behavior of miroalloyed steels and resultant surface quality condition. Different superheat practices have been recommended based upon the industrial sample test results. Since most casters worldwide operate between a 0.0001 and 0.001 strain rate through the unbending section of the straightening section, operating closer to the faster strain rate (0.001 through minor increases in casting speeds) enhances both the hot ductility performance and associated surface quality. Superheats exceeding 25°C are deleterious to surface quality regardless of the chemistry.

Each operation should thoroughly understand the specific 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, average residual levels and customer requirements.

REFERENCES

1 NAGASAKI, C.; AIZAWA, A; KIHARA, J. Influence of Manganese and Sulfur on Hot Ductility of Carbon Steels at High Strain Rate. *ISIJ Transactions,* vol.27, 1987, p. 506-512.

2 MINTZ, B.; The Influence of Composition on the Hot Ductility of steels and to the Problem of Transverse Cracking. *ISIJ International,* vol. 39, no. 9, 1999, p. 833-855.

3 MINTZ, B.; CROWTHER, D.N.; Hot Ductility of Steels and Its Relationship to the Problem of Transverse Cracking in Continuous Casting. *International Materials Review,* vol. 55, no. 2, 2010, p. 168-196.
4 JANSTO, S.; Effect of Melting and Casting Parameters on the Hot Ductility Behavior of Nb-Bearing Beams, Billets and Slabs. *AIST Proceedings-Volume II,* 2010, pp. 115- 125.
5 CHATTERJEE, A.; OJHA, C. C. Production of Quality Steels at Tata Steel. *Asia Steel*, p. 98-102, 1997.
6 JANSTO, S. G. Effect of Melting and Casting Parameters on the Hot Ductility Behavior of Nb-Bearing Beams, Billets and Slabs. *International Pipe Symposium-Moscow,Russia,* April 4-7, 2011.
7 JANSTO, S. G. Continuous Casting of Niobium-Bearing Steels Produced via the Basic Oxygen Furnace or Electric Arc Furnace Steelmaking Route. *European Continuous Casting Conference, METEC 2011,* Dusseldorf, Germany, June 27-July 1, 2011.
8 MISRA, S.; FRUEHAN, R. Hydrogen and Nitrogen Control in Ladle and Casting Operations. *ISS Tech Conference Proceedings*, p. 873-882, 2003.
9 MINTZ, B.; ABUSHOSHA, R.; AYYAD, S. Y.; CARDOS0, G. I. S. L. Cardoso, *HSLA '95, Proceedings of the Conference on HSLA Steels*, China Science and Technology Press, China, p. 342- 345, 1995.