Continuous Casting of Niobium-Bearing Steels Produced via Basic Oxygen Furnace or Electric Arc Furnace Steelmaking Route

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Abstract

High strength microalloyed steel product quality standards continue to become more stringent to meet ever-increasing customer requirements. Within the value-added steel sector, virtually all customers are tightening their specifications requiring less variability and lower acceptable residual elements. Customers demand more consistent mechanical properties, better steel cleanliness and improved surface and internal quality. There is a need for steel mills around the globe who expect to cost effectively produce high strength, high quality microalloyed automotive, pipeline and structural products to incorporate more disciplined steelmaking, clean steel ladle metallurgy and consistent continuous casting practices to successfully compete in today's global competitive market. This paper describes the Basic Oxygen Furnace (BOF), Electric Arc Furnace (EAF) and Secondary Ladle Metallurgy (SLM) steelmaking and casting considerations and recommendations that are being implemented today by steelmakers to successfully cast high quality Nb-bearing billets, slabs and beams. Cracking during casting is the direct result of steelmaking and caster practices related to residual chemistry, superheat variation, transfer ladle temperature stratification, mould flux incompatibility, casting speed fluctuation, and/or excessive secondary cooling. Often, the inherent hot ductility behaviour associated with a specific steel is misidentifed as the root cause. This paper will explore some of these root causes, which when corrected, minimize and/or eliminate cracking and improve surface quality, internal quality and overall yield across the entire product mix including higher carbon equivalent steels.

Introduction

Nearly 150 million tonnes of Nb-bearing steels were continuously cast globally in 2010. These Nb-bearing plate, bar and sheet products are manufactured at over 100 steel plants throughout the world. The majority of these mills consistently execute the melting and casting practices to assure the production of crack-free, high surface quality Nb, Nb-V, and Nb-V-Ti bearing steels. Much has been published about the traditional ductility trough and ferrite-film mechanism associated with cracking in these higher carbon equivalent grades of steels [1]. However, ductility trough data associated with simple carbon-manganese steels can also be tied to surface and internal quality issues if certain steelmaking and casting parameters are not followed. Although high carbon equivalent steels exhibit inherently lower hot ductility, as measured by percent reduction in area at elevated temperature, in many cases, these steels still exhibit sufficient ductility to satisfactorily meet the unbending stress and strain gradients existing in the straightening section of most casters.

An integration of the process metallurgy variables and the resultant physical metallurgy operative mechanisms which occur during the casting process must be studied to thoroughly understand the hot ductility mechanisms and process metallurgy controls and practices melt shops and casters employ today to produce high quality microalloyed steels.

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. Similar equipment processing of similar steel grades can result in varying degrees of slab, billet and bloom surface quality. 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. The optimal process and physical metallurgy combination and implementation aspects that are unique to each mill we call Metallurgical Operational Integration (MOI©) [2].

BOF and EAF Operations

The inherent differences between BOF and EAF operation that contribute to poor surface quality are well documented and understood. However, 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 in steelmaking operations involve: 1) nitrogen levels and variations, 2) residual levels such as copper, tin, etc. in the scrap, 3) tapping temperatures and resultant superheat and 4) excessive secondary cooling.

Figure 1 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 steelmaking and subsequent processing.

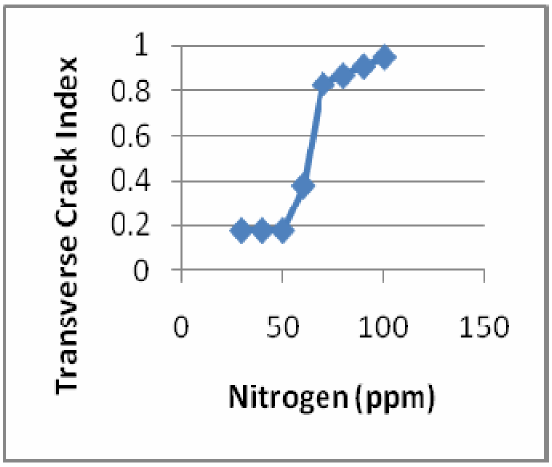

Figure 1: Effect of nitrogen on cracking index]3]

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 50 to 65ppm band which falls on the steep section of the curve which results in considerable variation in surface quality results and 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 function.

Current BOF practices to obtain consistent N levels less than 50 to 60ppm for integrated steelmaking include:

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.

The majority of EAF produced 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 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.

After tapping into the secondary ladle metallurgy operation, the following practices may affect nitrogen levels and hence, hot ductility behaviour 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).

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. These variables include transfer pour time, 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 beam mill producing low carbon Nb-bearing steel, the area percent of the equiaxed zone in the cross-section of the beam blank is found to decrease with an increase in superheat temperature. Simultaneously, the degree of centreline 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 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 [4].

For example, if the steel superheat is too high, then the centreline 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 might need 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.

Other Continuous Casting Operational & Maintenance Considerations

The continuous casting of crack free Nb-bearing low carbon and high carbon equivalent grades is achieved through the application of appropriate casting practices and chemistries. If the chemistry recommendations and metallurgical considerations discussed earlier in this report have been validated and quality is still an issue, then the root cause may be related to one or several of the following causes [5]:

1) Heat transfer characteristics

a) heat transfer of mould powder

b) mould level control performance

c) consistency of mould powder feed

4) reduce temperature of secondary cooling water to keep slab/billet/beam blank corners above 900°C

2) Caster and mould design

a) mould face taper

b) oscillation mark depth and crack depth relationship

c) strain rates based on metallurgical radii and carbon equivalent

d) oscillation mark grid profiles.

3) Preventative maintenance issues

a) cooling headers and nozzle pressures and temperatures

b) water quality cleanliness and hardness

c) water temperature and variation from loose to tight side of the strand

d) strand segment alignment via laser scan

e) roll gap and wear history

f) soft reduction performance.

4) Melting and ladle temperature control

a) hot ductility trough issues related to high sulphur

b) ladle temperature stratification during teeming

c) excess superheat (greater than 20°C)

d) superheat variations during cast

5) Scarfing induced cracks

a) inadequate standard

b) operating practices

c) inexperienced operators introducing cracks on high equivalent steel grades.

Effect of Secondary Cooling on Hot Ductility

Spray cooling practices have a significant effect on the depth of the equiaxed zone, strand behaviour through the straightening section and overall surface quality. Thermal stresses are generated in the slab or billet due to the surface cooling and recalescence between each successive spray nozzle. The mechanical stresses are from the bulging of the cast strand due to ferrostatic pressure between the rolls.

In numerous casters around the world, the secondary cooling practices are nearly the same regardless of the carbon equivalent. Typically the operational practices are more concerned with reducing the casting speed on higher carbon equivalent and microalloyed grades containing Nb, Ti and/or V compared to simple carbon manganese grades (such as S235) without making an appropriate decrease in secondary cooling to reduce the heat transfer. This condition becomes a major challenge for mills with older casters which are not equipped with speed/secondary cooling water control interfaces in their computer model software.

Actually, slowing down the caster speed for high carbon equivalent grades (exceeding 0.35%) by 15-20% is actually the opposite adjustment that should be made to minimize cracking. These speed adjustments can double or triple the cooling rates in the secondary cooling section making an extremely thin equiaxed layer in the cast strand. With equiaxed layers as thin as 10 mm on a 200mm thick slab, surface quality issues and a propensity for cracking increases dramatically.

Within the secondary cooling section, hot ductility data indicates some significant improvements in ductility when reducing the cooling rate from 200°C/minute to 50°C/minute. Figure 2 illustrates this effect of reducing the cooling rate and the significant improvement in hot ductility at the recommended operating window for straightening (unbending) between 850°C and 900°C.

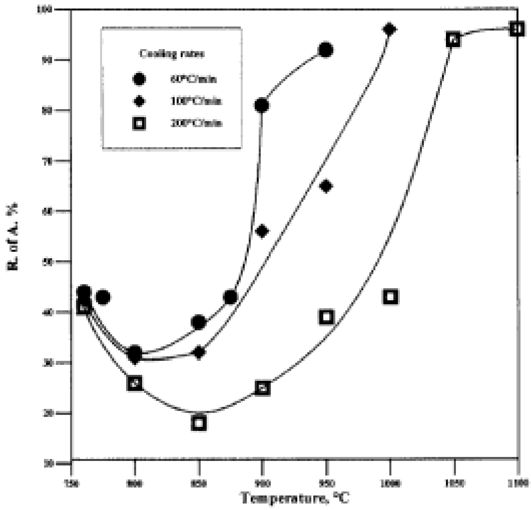

Figure 2: High versus low secondary cooling rate [6]

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. Also, the thickness of the equiaxed chill zone is smaller. 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%.

Effect of Strain Rate on Hot Ductility

The prior section described the inappropriate practice at some mills that reduce the caster speed on microalloyed or higher carbon equivalent grades to improve surface quality. In such cases, surface quality may not improve resulting in an undesired reduction in productivity.

Fundamentally, higher strain rates can actually narrow and move the ductility curve to higher % RA as illustrated in Table 1 and Figure 3 for a Nb-bearing steel.

Table 1: Nb-steel chemistry

C	Mn	Si	P	S	Al	Ni	Nb	N	O
.063	1.35	0.52	.025	.004	.03	.20	.04	.006	.003

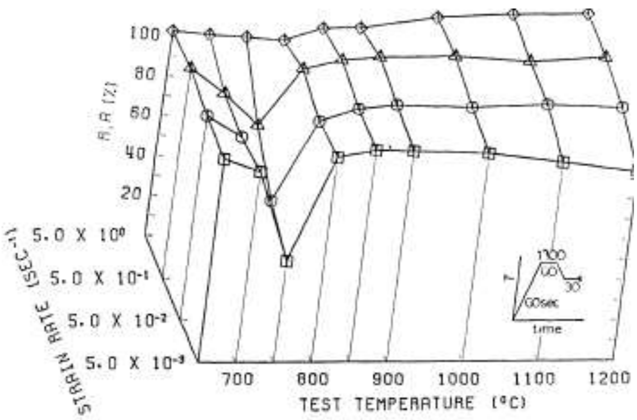

Figure 3: Dependence of strain rate and temperature on hot ductility of Nb-bearing steels [7]

Fundamental Factors Affecting Hot Ductility

Before considering the effects of chemistry, it is important to understand the four major factors that affect the hot ductility curve shape at the microstructural level. An understanding of these mechanisms at numerous mills has resulted in the successful production of over 150 million tons of cast Nb-bearing steels. Keeping these four factors at the forefront of the caster operation and practices is the key to high productivity and excellent quality. The four major factors that control hot ductility are: 1) strain rate, 2) grain size, 3) precipitation and 4) inclusion content.

Already discussed in the previous section is the increase in hot ductility at increased strain rates. Refinement of the grain size through the achievement of a fine (generally 200μm) and deep equiaxed grain size will reduce the amount of grain boundary sliding as the bloom is straightened. Typically, equiaxed grain zones are 10 to 25 mm thick depending upon the bloom thickness and the upper segment cooling and secondary cooling conditions.

The other two variables which have a major influence on the hot ductility behaviour through the straightening section are precipitate size, chemistry and morphology and the volume of inclusions. For example, for a given volume of precipitates and/or inclusions, the finer the particles at the boundaries, then the closer they are to each other and the easier it is for a crack to interlink.

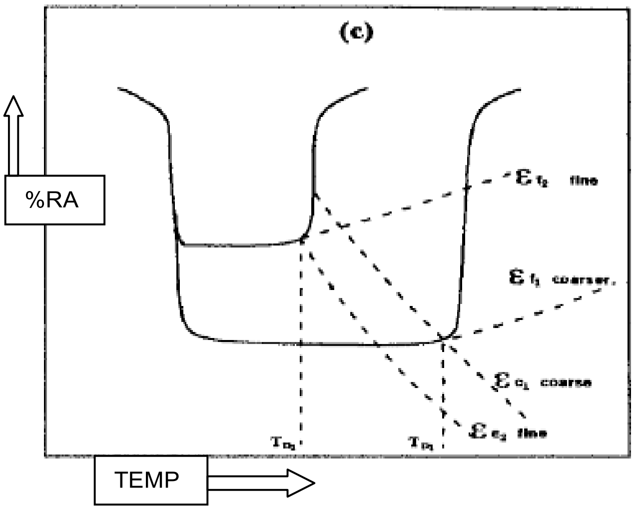

Figure 4: Relationship between hot ductility trough and precipitate and inclusion size [8]

Therefore control of the steel internal cleanliness and efficient secondary ladle metallurgy is necessary to control sulphur and residual levels to reduce the overall volume fraction of inclusions.

Effect of Composition

The effect of sulphur, nitrogen and residual elements have a direct relationship with the hot ductility behaviour of microalloyed grades of steel.

Sulfur Effect on Hot Ductility Behavior

The relationship of an element to the deleterious effect on the hot ductility are sulphur to nitrogen to residual elements. Increased levels of sulfur increase the extent of potential susceptibility to surface cracking during steel processing at high temperature. It also increases the inclusion level which adversely affects the physical and mechanical properties of the finished product. Therefore, the concentration of sulfur must be carefully controlled and kept as low as possible (except in machining grades.)

For critical grades, the hot metal delivered from the blast furnace is controlled to a maximum of 0.015%S. Steel ladle desulfurization with calcium silicide further decreases S levels generally between 0.003% and 0.009%S. In some cases involving Nb-bearing grades, the manganese sulphide(MnS) inclusions are the root cause for reduced ductility. In general, MnS inclusions are associated with intergranular fracture. Nb-bearing steels are sensitive to the amount of S in solution which is able to segregate to the grain boundaries. As the S concentration increases, the hot ductility behaviour as measured by percent reduction of area decreases.

Figure 5 below illustrates the relative change in ductility in relation to high (0.015%S) and low (0.005%) sulphur levels in a Nb bearing steel.

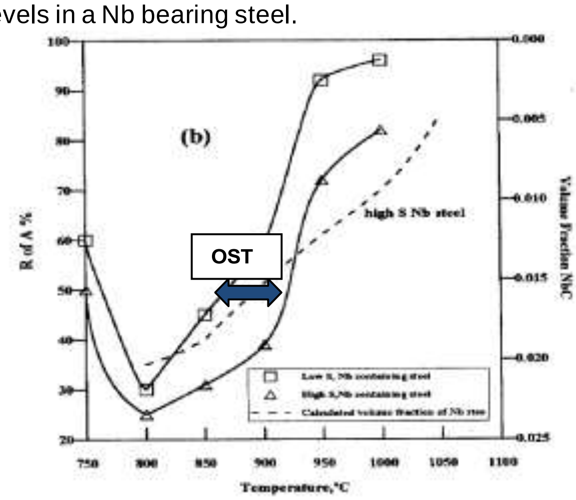

Figure 5: Sulfur effect on hot ductility [9]

The magnitude of the reduction in hot ductility between high sulphur versus low sulphur steels decreases as straightening temperature decreases. The optimum straightening temperature (OCT) for Nb-bearing steels is between 850°C to 900°C. Table 2 below relates these differences in hot ductility behaviour for high and low sulphur Nb-bearing steels.

Table 2: Reduction of area (%) versus temperature

	750°C	800°C	850°C	900°C
High S	46%	24%	30%	38%
Low S	60%	30%	45%	60%

Sulfur increases the extent of surface cracking during steel processing at high temperatures and affects the resultant hot ductility behaviour in the straightening section of the caster. Table 2 exhibits the significant increase in ductility at 850 and 900°C. However, if the unbending section (straightening section) is in the vicinity of 800°C, the low sulphur approach will be less effective in minimizing the propensity of cracking. Hence, the straightening temperature window at the caster of 850°C to 900°C for Nb-bearing grades of steel is recommended.

As presented in Figure 4, finer precipitates and inclusion size improve hot ductility behaviour. Therefore, it is important to limit and control the volume fraction and distribution of MnS inclusions. High sulphur concentrations adversely affect the ductility of the cast strand as well as the mechanical properties of the finished product. Therefore, the concentration of sulphur must be controlled and kept as low as possible (except in machining grades). For critical grades of steel, the steel is tapped from the BOF at a maximum 0.015%S. Steel ladle desulfurization with calcium silicide is employed to further decrease the S levels between 0,003%- 0.009%S.

In some cases involving Nb-bearing cast grades, the manganese sulphide inclusions are the root cause for the reduced ductility and incipient cracking. In general, MnS are associated with intergranular fracture evident in fractographic analysis of cracked slabs. Nb-bearing steels are sensitive to the amount of S in solution which can segregate to the grain boundaries and reduce the percent reduction in area at temperature.

Nitrogen Effect on Hot Ductility Behavior

Nitrogen has been universally accepted as detrimental to hot ductility in aluminium killed microalloyed steels. Thus, in order to minimize cracking, the N levels should be kept as low as possible. However, with the increased use of HSLA scrap and nearly half of the global steel production via the EAF steelmaking route, the effects of higher nitrogen levels (greater than 90ppm) on the castability and hot ductility behaviour through the straightening section have received much attention.

With appropriate process metallurgical caster practices, high nitrogen bearing steel grades are currently being successfully cast in slab, thin slab, billet and near net shape beams with minimal or no transverse cracking around the world. The key involves tight control of the soluble Al. Generally, for Nb-bearing grades, maintaining a 0.02-0.04%Al (aiming for the minimum at 40ppm N BOF steel and 65ppm at the EAF) and a 5 to 1 Al:N stoichiometric ratio suffices to minimize and, in most cases, eliminate cracking. These results have been substantiated via the review of surface quality on industrially produced Al-killed Nb-bearing steels. The relationship between Al and N and hot ductility in a non-microalloyed steel is illustrated next in Figure 6.

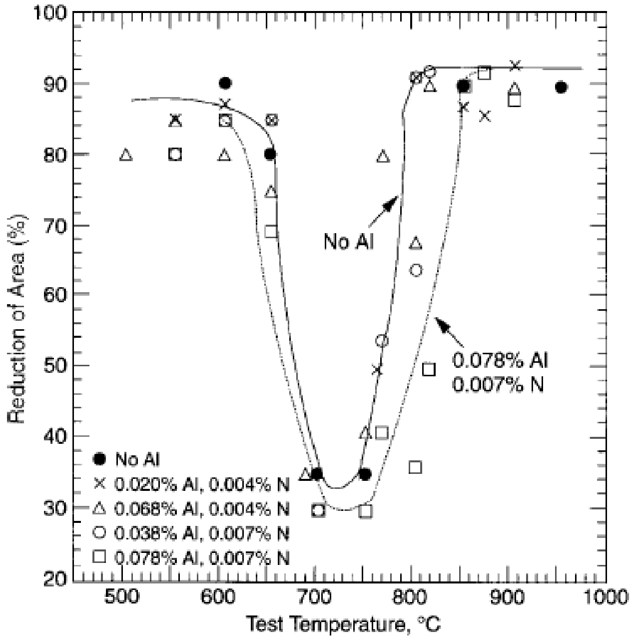

Figure 6: Effect of Al-N on hot ductility [10]

It should be noted in the above figure that when straightening temperatures are above 850°C the change in hot ductility as measured in percent reduction in area exceeds 85% for both nitrogen levels. Many casters have unbending temperatures between 750-850°C which is in the steepest slope region of the hot ductility curve for simple C-Mn steels. Temperature variations through the unbending section or the ΔT between cold corners or edges and the broad face can generate residual thermal stresses. Consequently, depending upon the superheat and temperature variation during casting, the ΔT through the unbending section will affect slab surface quality and its propensity for transverse cracking. Note that in a conventional caster, a ±10°C temperature variation through the straightening section results in a ±5% fluctuation in hot ductility and typically presents no problem with surface quality.

Microalloy Effect on Hot Ductility Behavior

Numerous papers have been published (some are referenced in this paper) describing the effect of microalloys, such as Nb, Ti and V, on the hot ductility behaviour of low carbon steels. The deeper troughs with microalloyed steels are generally related to the reduced hot ductility (percent reduction in area of 20 to 30%) and so identified as the root cause for transverse cracking in the unbending section of casters. However, from an industrial perspective, several hundred million tonnes of microalloyed steels are produced defect-free. For example in 2010, nearly 150mm tonnes of Nb-bearing slabs, billets and blooms were successfully cast with prime surface quality. Following numerous investigations throughout the world, it is apparent that the incidence of transverse cracking is more process metallurgy-driven with the physical metallurgy dictating the cracking mechanism when four key process operational furnace and/or caster variables are outside their upper and lower control limits.

Major BOF and EAF Process Metallurgy Variables Affecting Transverse Cracking

Although well known, the casting of microalloyed steels requires closer operational attention is compared to casting of standard C-Mn grades. The following process metallurgy variables require more attention in microalloyed steels since they affect the hot ductility of an industrial caster operation [11]:

1) Minimization of nitrogen variation from heat-to-heat (see Figure1).

2) Control absolute value of superheat not to exceed 20°C.

3) Limit superheat variations since a condition exceeding ±10°C fluctuation may initiate from ladle temperature stratification during teeming.

4) Avoid excessive cooling rates in the upper caster segment and in the secondary cooling section. This condition leads to thin equiaxed grain zones that are weak under imposed stress during unbending.

Excessive ladle transfer times and treatment times increase probability for ladle temperature stratification and possible segregation and propensity for cracking. A standard procedure that correlates the magnitude of centreline segregation to the transverse cracking index should be tracked and statistically evaluated for statistical process control purposes. In many instances, a caster that exhibits a high degree of centreline segregation will tend to exhibit a higher propensity for transverse crack incidence. Many casters today are equipped with soft reduction capability which minimizes chemical segregation in the bloom.

The other important consideration involves the addition of titanium in Nb-bearing steels. Alloying with titanium must be carefully controlled. The titanium is added to stabilize the nitrogen at approximately a 3.0 to 3.2 Ti:N ratio. When N varies from heat-to-heat, the proper stoichiometric ratio must be made based upon the measured N. Figure 7 next shows the influence of on hot ductility if there is a sub-stoichiometric Ti:N ratio or nil Ti and the effect on the ductility trough for .007%Nb-C-Mn steel.

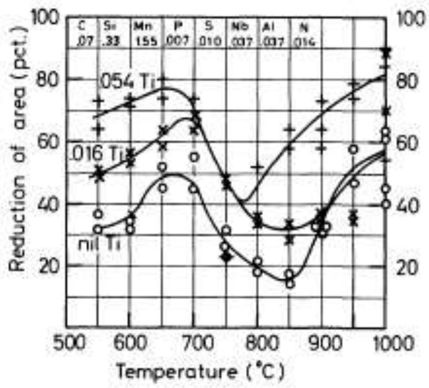

Figure 7: Effect of Ti:N ratio on hot ductility [12]

Soft Reduction

Soft reduction is quite advantageous for improving the quality of Nb-bearing slabs, billets and blooms. Casters which are designed with soft reduction capability and proper operational control may produce cast strands of higher quality than some casters lacking soft reduction capability. 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 within this paper. The soft reduction breaks up the interdendritic bridges formed during solidification and minimizes macrosegregation. The hot ductility trough is actually narrowed and raised to higher percent reduction in area levels.

The optimal process parameters for each mill will vary depending upon caster design, composition of steel grades and steel temperature practices. 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.

Conclusions

The casting of high quality Nb-bearing steels is an integration of the melt shop process metallurgy and control and the continuous caster process control as has been demonstrated globally through the production of over 150 million tonnes of high quality Nb-bearing steel. The control of the nitrogen, sulfur and residual chemistry levels, as well as their respective variations, is important due to their effect on the hot ductility behaviour. EAF operations are introducing alternative metallic input materials to dilute the residuals thereby improving the hot ductility behaviour.

Several process metallurgy parameters significantly affect the hot ductility behaviour. However, the two primary drivers involve superheat control and secondary cooling. The total superheat should be controlled to less than 20°C for microalloy steel heats. 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. The optimized chill zone depth is maintained 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, sulfur levels and primary/secondary cooling flow rates.

With respect to the wide range of slab sizes, shapes and chemistries and caster designs and capabilities, each mill is unique. No universal solution can be specified; however the process metallurgy considerations are an important element in the successful casting of Nb-bearing and other high value, microalloyed grades of steels

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