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CARBON CONTENT, SOLIDIFICATION AND STRAIN ENERGY PHENOMENA AFFECTING HOT DUCTILITY BEHAVIOR DURING CONTINUOUS CASTING OF MICROALLOY STEELS

Abstract

Superior continuous cast bloom quality is critical in order to achieve the high quality strength and toughness balance required for today's demanding bar, plate and sheet applications. Continuous casting parameters, such as super heat, mold level fluctuation, heat transfer, fine grain chill zone depth and other process performance parameters directly influence solidification behavior and hence the surface and internal quality of the steel strand. This research identifies that the traditional hot ductility as measured via the percent reduction in area (%RA) at elevated temperature grossly overstates the minimum ductility required to assure crack-free casting of micro alloyed steels. Strain energy measured from industrial heat sample stress and strain curves are a better measure of the hot ductility behavior than %RA. The strain at the ultimate tensile strength exhibits a very high correlation coefficient with strain energy and extremely low correlation coefficient with %RA. The carbon content, fine grain chill zone depth and strain energy directly govern hot ductility behavior and the propensity for crack formation during the unbending phase of the continuous casting process. Elements other than carbon and micro alloys exhibit secondary or tertiary root causes for crack formation.

Keywords

Equiaxed-columnar grain transition zone, Mixed grain, Residual strain, Strain energy

1. Introduction

There are several published papers based upon the relevance of the traditional hot ductility trough associated with higher carbon equivalent steels with and without microalloy additions of Nb, V and/or Ti. This extensive research has been performed in an attempt to relate the steel chemistry to the hot ductility behavior of low and medium carbon microalloyed steels [1,2]. The early research focus by others has primarily studied the chemistry and optimal composition suggested in order to increase the percent reduction in area during the unbending of the continuous cast slab, thereby raising the ductility trough. Although the emphasis on chemistry has been well studied, the steelmaking, solidification dynamics and process metallurgy parameters of the actual steelmaking operations are rarely correlated to the hot ductility behavior and resultant slab surface quality. In addition, most studies involve laboratory produced heats whereas this research is based solely upon industrial produced samples with an emphasis on process parameters and solidification at different carbon levels.

This research shows that high carbon equivalent microalloyed steels which exhibit inherently lower hot ductility, as measured by percent reduction in area at elevated temperature still demonstrate sufficient ductility to satisfactorily meet the unbending stress

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and strain gradients in the caster. Published percent reduction in area (%RA) data significantly overstates the minimum ductility required for crack-free casting of Nb-bearing steels by two to threefold. The measure of %RA as a correlation to the propensity for cracking during casting is very weak. This study shows that the reason for this lack of correlation is due to the relationship between the steelmaking and caster operation affecting solidification and the depth of the equiaxed chill zone. Process metallurgy variables are the primary driver of the resultant slab quality and its hot ductility behavior. It is proposed and validated through this study that the strain energy is a better measure of predicting the hot ductility behavior during the continuous casting of slabs rather than the %RA measurement.

The relationship between the carbon level of the steel and heat transfer rate conditions for solidification affects the solidified microstructure and the thickness of the equiaxed chill zone. At some distance below the surface where the chill zone ends, there exists an equiaxed columnar grain transition zone (EACLG). This zone is a mixed grain microstructure and hence, a zone of high residual strain. On the opposite end of the EACLG exists the initiation of the columnar grain microstructure. The closer the EACLG transition zone is to the surface then the probability of the mixed grain generating a crack through the unbending section of the caster increases regardless of the microalloy content.

2. Solidification

Carbon steels with a hypo-peritectic composition (carbon content between 0.11 and 0.16 wt.%), show higher surface crack susceptibility when they are produced by the continuous casting process [3,4]. This susceptibility is usually attributed to a volumetric contraction previously discussed associated with the peritectic solidification phenomena, which is described by the reaction:

$$\text{liquid (L)} + \text{primary phase } (\delta) \rightarrow \text{secondary phase } (\gamma) \text{ [5-8]} \quad (1)$$

The peritectic transformation supports large austenitic grains resulting in brittle material behavior during solidification. That means, in a temperature range between Ae3 and approximately 1100°C, the solidified shell material can easily be damaged and a crack growth along the grain boundaries can occur without any big plastic deformation. Additionally, high stresses are introduced during the early solidification. A strong shrinkage takes place during the phase change from the δ-ferrite to the tighter arranged γ-austenite structure [9]. Hypo-peritectic grades often results in unstable operating conditions (mold level hunting, cast breakouts) and defective slab products (rough surface and deep oscillation marks, surface cracks both in longitudinal and transversal direction). Although at times, may be possible to avoid the peritectic reaction by suitable alloying additions, it is easy to push a non-peritectic steel into the peritectic range by missing the carbon aim which is dependent upon a given Basic Oxygen Furnace (BOF) or Electric Arc Furnace (EAF) carbon reduction control practices. If carbon scatter from heat-to-heat occurs, without adjustments during the hot rolling mill, the rolled steel will exhibit variable mechanical properties, weldability and formability.

Surface quality deterioration leads to increased conditioning costs, rework and rejects. This non-uniformity in the chill zone results in hot spots/hot seams, and hence the occurrence of short longitudinal facial cracks. One critical operational practice is the mold flux used in peritectic grades as it enhances cuspidine crystallization in the mold flux film. This film is considered most promising to decrease the cracks since it reduces both radiation- and conduction-heat transfer from the shell to mold near the meniscus and assists in forming a uniform shell [10]. However, increased cost is associated with the adjustments and mould flux necessary to compensate for the probable surface defects from improper temperature control during casting.

3. Equiaxed Columnar Grain Transition Zone Mechanism

In rare cases when other researchers did collect industrial continuous cast slab samples for hot ductility tests, a detailed sketch of the actual sample location and orientation within the slab is often not reported. For example, centreline samples for hot ductility behaviour would be affected by segregation versus surface samples or sub-surface samples which might exhibit an equiaxed or mixed grain or columnar microstructure. In this research, the intent is to determine the hot ductility behaviour sub-surface at or near the transition in grain size from the equiaxed chill zone to the columnar grain zone. This mixed grain zone represents a variable grain size due to the solidification rate. As a result of the grain mismatch in the transition zone, a high residual strain region exists some distance below the surface. This zone can be quite closer to the surface due to the solidification phenomena for hypo eutectoid steels compared to lower or higher carbon steels. Also, the cooling conditions in the upper section of the mould directly affect the thickness of the equiaxed chill zone. Upon solidification, the equiaxed chill zone is usually between 10 to 25mm below the surface depending upon the slab thickness being cast, casting speed, primary cooling rate and the associated heat transfer rate. Figure 1 below illustrates the transition zone form the equiaxed chill zone at the surface continuing some depth into the sub-surface, followed by the transition zone and then the columnar zone.

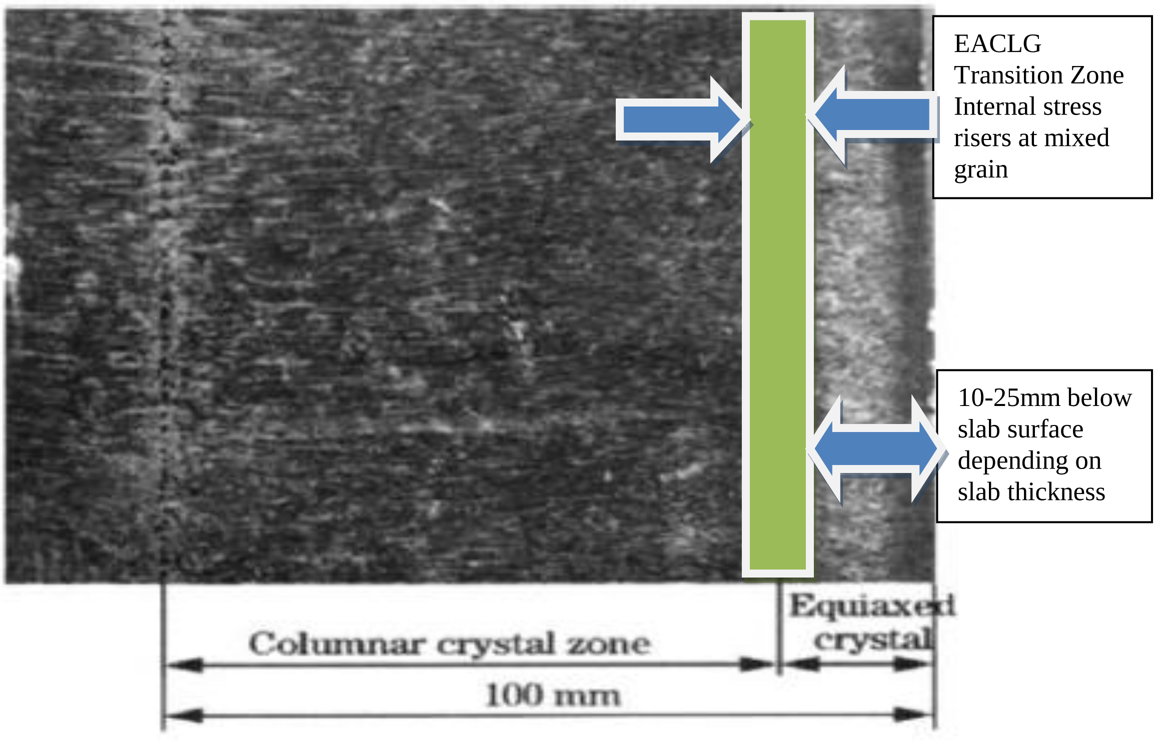

Fig. 1. Eqiuaxed Columnar Grain Transition Zone (EACLG)

It is this subsurface EACLG transition zone that creates the residual stress due to the mixed grain region where the equiaxed fine grain chill zone ends and the dendritic columnar zone is beginning to nucleate and grow. Figure 2 schematically represents the difference between microalloy and/or non-microalloyed hypo-peritectic grades and higher or lower carbon and peritectic grades.

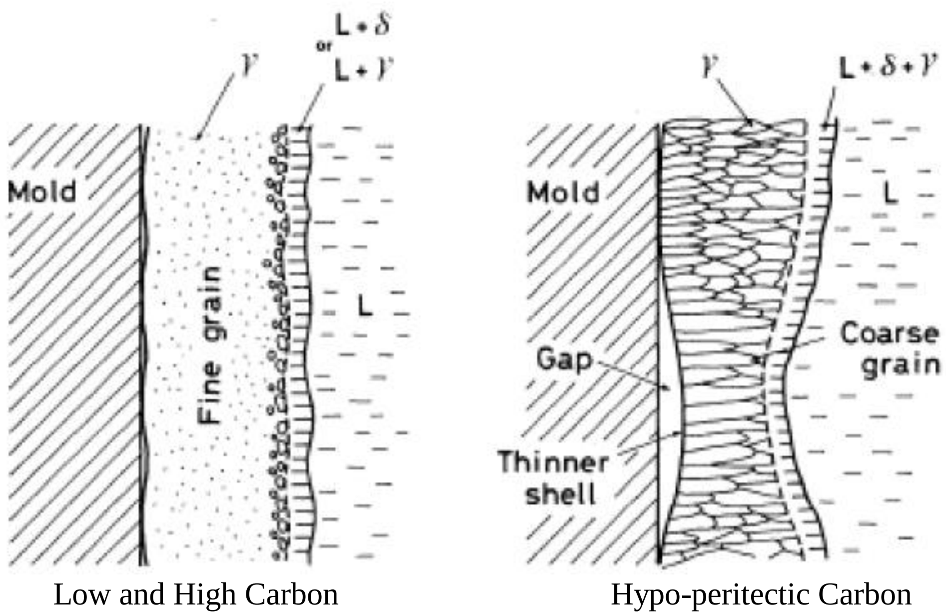

Fig. 2. Comparison of fine grain chill zone and limited or no chill zone

The influence of mixed grain on the yield and tensile behavior and the shape of the stress strain curve was examined with samples obtained from the EACLZ for various carbon grades. The samples obtained for the stress and strain curve evaluation in this study came for the sub-surface EACLG transition zone of industrially cast slabs as shown in Figure 3.

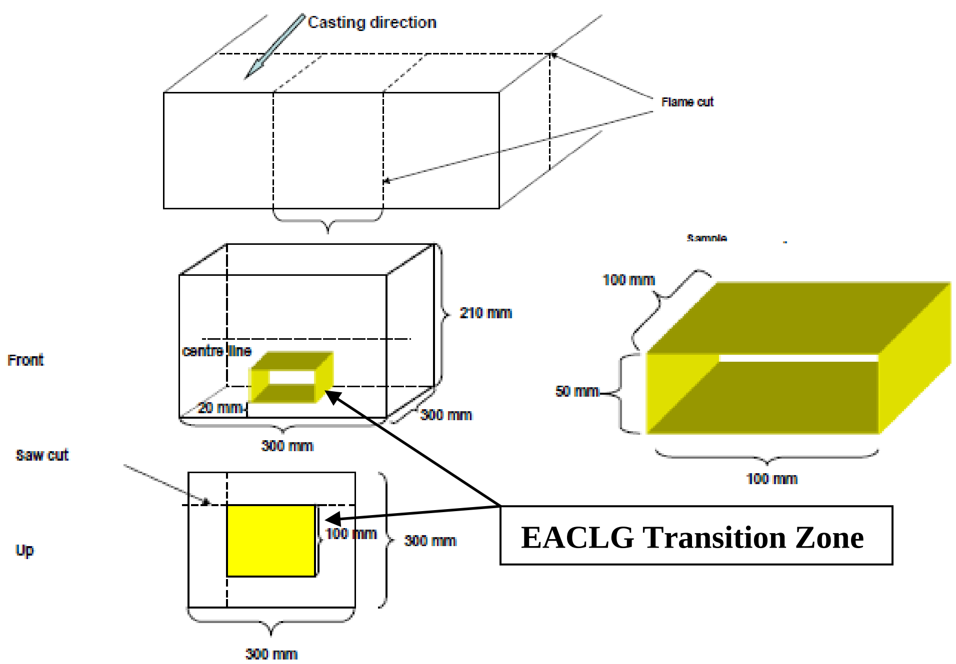

Fig. 3. Sample location from EACLG transition zone

3. Unbending Section of Caster and Imposed Unbending Section Stress on EACLG

The unbending section of the continuous caster imposes the highest strain on the solidifying section of the slab or billet as it is processed. The strain is directly related to the metalllurgical radius of the caster which varies from mill to mill. The smaller the metallurgical radius (i.e. curvature of the bend) then the higher the imposed strain on the solidiying strand. Figure 4 below illustrates the location of the unbending section of the caster.

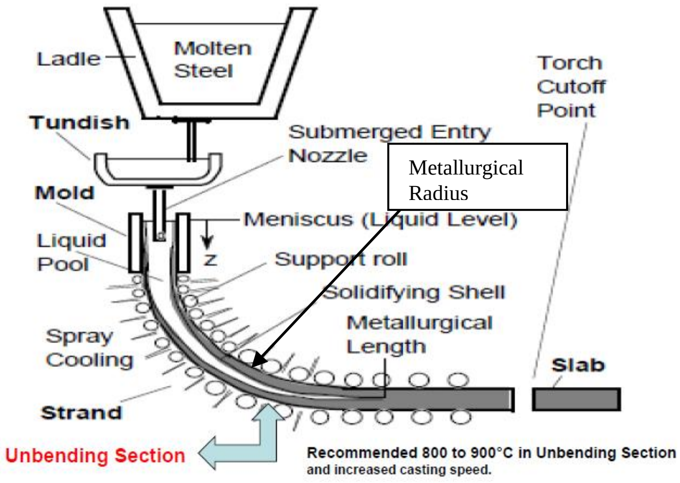

Fig. 4. Unbending section of continuous caster

Since the typical temperature through the unbending section of the caster is between 700 to 950°C, most of the hot ductility %RA research has been in this temperature range. The hot tensile tests are performed within this temperature range at strain rates between 0.001 to 0.0001 mm/mm/second for this stress-strain curve hot tensile test analysis. This strain rate simulates the strain rates induced within the unbending section of industrial casters at typical casting speeds for microalloyed steels. The ductility trough in this example is between 750-800°C with approximately 20-25%RA at strain rates of 0.0001 to 0.001 mm/mm/sec. Most industrial casters operate at casting speeds through the straightening section with a strain rate during unbending between 0.0001 to 0.001 mm/mm/sec strain rate.

4. Mechanical Hot Ductility Test Program

Hot tensile tests were performed on a Gleeble 3500 thermomechanical system. The industrial steel samples were heated to 1300°C at a heating rate of 10°C/sec and held for 5 minutes to assure that the microalloy precipitates went back into solution. The cooling rates are at 60°K/minute to the test temperature simulates the actual casting conditions through the unbending section of the industrial casters that produced the steel samples. Thermocouples on this unit provide signals for accurate feedback control of specimen temperatures. Specimens are clamped securely and tightened by hand in the test chamber of the Gleeble 3500 thermo-mechanical tester. The machined specimens are seated between two water-cooled copper jaws located nearby the specimen threads. Test temperatures were between 700 to 950°C to simulate straightening (unbending) temperatures at the industrial casters who provided samples. Strain rates simulated the actual operational strain rate at the caster (i.e. between 0.001 and 0.0001 mm/mm/second). All hot tensile tests were performed on a Gleeble 3500 model. Figure 5 below schematically presents the heating and cooling schedule for an 800°C test temperature example.

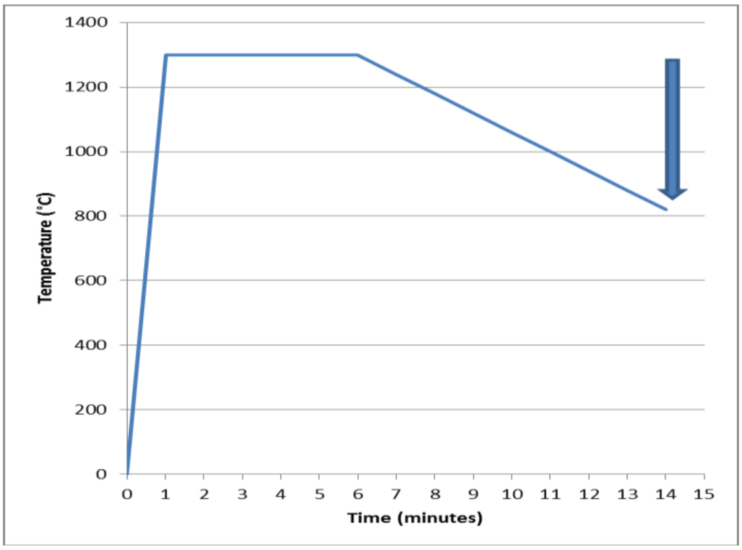

Fig. 5. Heating & cooling schedule example for 800°C test at two strain rates (0.001 mm/mm/sec and 0.0001mm/mm/sec).

The strain rates for all of the tests simulated the actual operational strain rate at the unbending section of the casters' providing the samples for this study. The two strain rates employed were between 0.001 and 0.0001 mm/mm/second. The raw data output of force, dynamic gauge measurements, stress and strain were converted into a stress strain curve for each sample. Figure 6 is an example for one chemistry which illustrates the stress strain curve at 800°C for a 0.16%C-1.45%Mn and 0.04%Nb chemistry at 0.0001 and 0.001 strain rate.

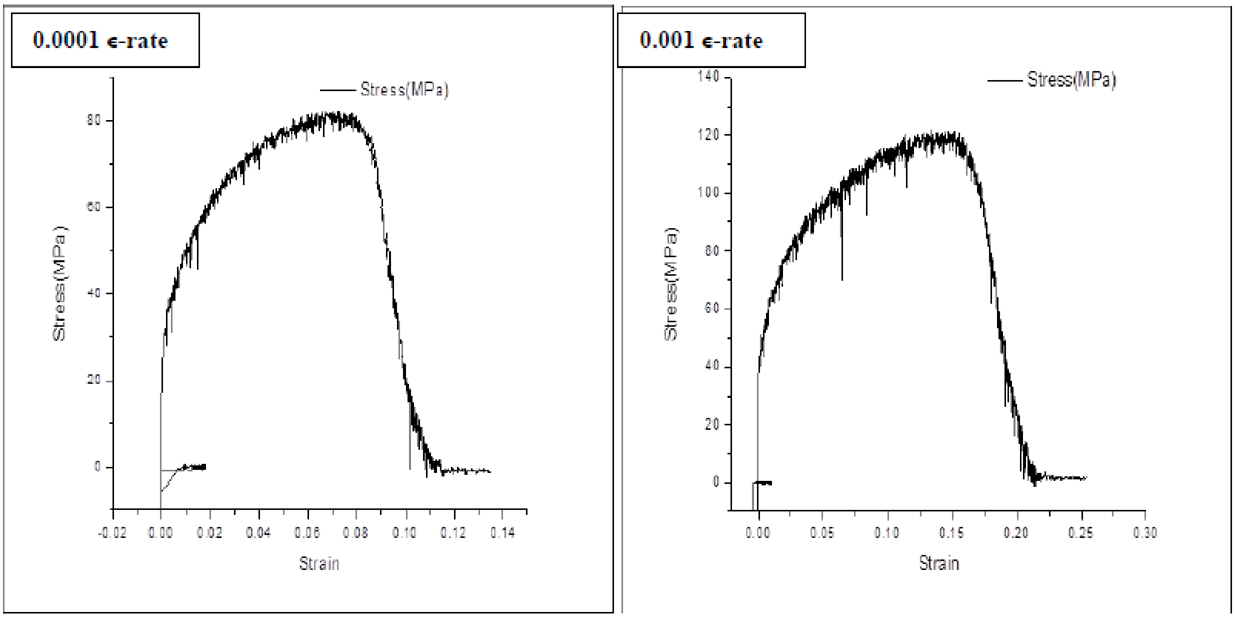

Fig.6. Stress strain curve (sample 1A at 800°C and 0.0001 (left) & 0.001 strain rate (right).

Note that at the higher strain rate, the ultimate tensile strength is 120MPa versus 80MPa (at the lower strain rate) and 0.155 strain versus 0.068 strain at UTS respectively. The strain at fracture for the 0.001 strain rate is 0.254 versus 0.135 for the lower strain rate of 0.0001. The area under the σ-ε curve up to a given value of strain is defined as the total mechanical energy per unit volume (U*) consumed by a material in the process of straining to that given value. This equation is shown by:

$$U^* = 1/V\int_0^L (P/A_0)(dL/L_0) = \int_0^L \sigma d\varepsilon \qquad (2)$$

In the absence of slip and other mechanisms for energy dissipation, this mechanical energy is stored reversibly within the material as strain energy. The strain energy increases quadratically with the stress or strain (i.e. as the strain increases then the energy stored by a given increment of additional strain grows as the square of the strain). The area up to the yield point is termed the modulus of resilience. The total area up to fracture is termed the modulus of toughness. The strain energy is then calculated by integration of the area under the stress-strain curve in Figure 6 and compared to the %RA data (Table I below).

Table I. Strain Energy, Strain at Ultimate Tensile Strength and % Reduction in Area

Strain rate (mm/mm/sec)	0.0001	0.001
Strain energy (MPa-mm/mm)	6.663	19.380
%Reduction in area	14.5	27.6
Strain at UltimateTensile Strength	.068	.155
Strain at Fracture	.135	.254

This strain energy approach and evaluation of the strain at UTS and fracture has not been considered in the field of hot ductility behavior of continuous cast steels through the unbending section of the casting. Thus, this research introduces the strain energy and stress strain curve relationship to hot ductility behavior and the related significant processing variables that affect solidification and better predicts propensity for craks during unbending.

5. Strain Energy and %RA Relationship to Strain at Ultimate Tensile Strength

Evaluation of several hundred samples at different hot tensile test temperatures resulted in the derivation of the strain energy as described in Equation 2 and the traditional %RA. this research determined that the minimum required %RA for crack-free casting is inaccurate and significantly overstates the %RA required for crack-free castability. For example, the literature quotes 40% RA minimum for Nb-bearing steels when in fact as low as 10% minimum RA is more than sufficient to assure crack-free casting based upon the extensive testing, operational parameter review and analysis performed in this study. Based upon this reported minimum 40%RA [11] for crack-free casting, the implications have resulted in some alloy developers reducing or totally eliminating the selection of Nb for a new carbon steel development due to this published 40 %RA minimum casting criterion. This situation stimulated the examination of the stress strain curve, strain at UTS and fracture and strain energy for different steels at different unbending temperatures. A regression analysis was then performed on the data. For example, at a 800°C unbending temperature, the %RA and strain energy was evaluated and plotted against the measured strain at the ultimate tensile strength. A comparison of these measures is shown below in Figure 7 and 8.

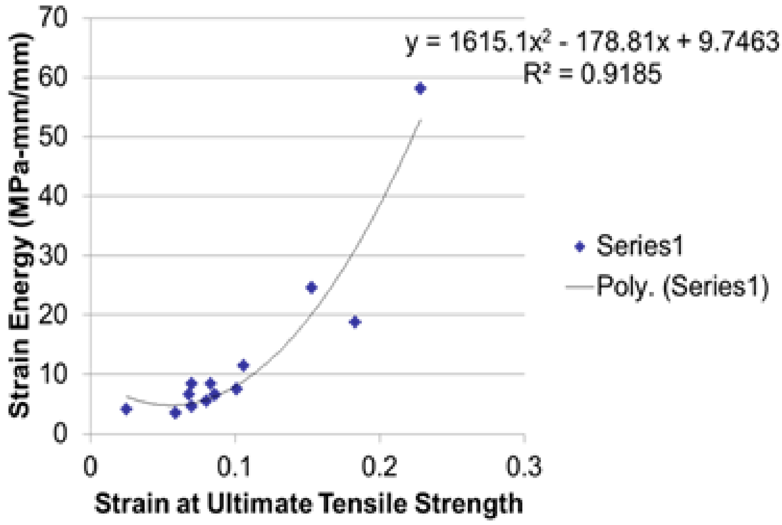

Fig.7. Strain energy versus strain at ultimate tensile strength

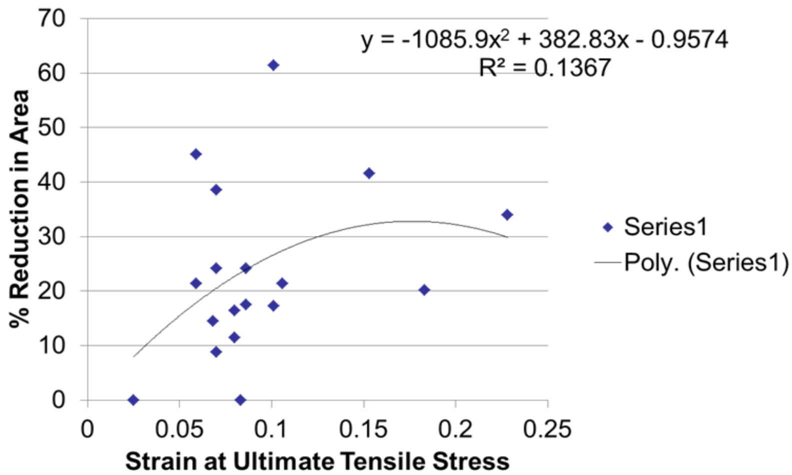

Fig.8. Percent reduction in area versus strain at ultimate tensile strength

The r-squared correlation coefficients are very high for the strain energy at 0.9185 compared to the very low r-squared of 0.1367 for the % reduction in area versus the strain at the ultimate tensile strength. Data is calculated from the hot tensile stress strain curve database generated from several hundred industrial samples tested at unbending temperatures between 700 and 950°C. The results substantiate the very inconsistent assessment of %RA and crack initiation. The more effective strain energy measure of hot ductility is proposed as an improved test method to assess potential hot ductility behavior of steels.

6. Unbending Strain, EACLG and Strain at Ultimate Tensile Strength (UTS)

The relevance of the relationship between the strain at the UTS for a given chemistry, propensity for cracking during the unbending of the strand and the location of the EACLG transition zone interconnect. In many cases, continuous cast defects are sub-surface and historically the reason for conditioning and/or oxygen scarfing of slabs and billets to reveal the defects that are hidden sub-surface. The residual sub-surface strain in the slab will interact with the external imposed strain during unbending. However, through the years of research, heavy focus has been on the physical metallurgy of the austenite grain size, ferrite film chemistry and precipitates evident near or at the crack. Also, other researchers heavily focused upon water modelling, turbulence and fluid flow. The intent of this work is the residual strain of the sub-surface mixed microstructure and variable grain size and morphology prior to entering the unbending section with a focus on solidification. The hypothesis does include the relationship between an EACLG transition zone that is closer to the surface due to solidification conditions, then the accommodated strain at the UTS would be lower and the propensity for cracking would be higher.

Generally speaking, grain size [12,13], grain orientation [14], orientation of neighbouring grains [15] and the presence of grain boundaries will influence the local material response leading to heterogeneous stress and strain fields at the microstructural scale. It is also well established that the grain boundaries are particularly important in the crack initiation and propagation mechanism and their role has been a subject of extensive research [16]. Certainly, the inhomogeneity of grain size and the inhomogeneous accommodation of the imposed stress and deformation in the vicinity of grain boundaries in cast slabs require more study.

7. Process Metallurgy Parameters and EACLG Transition Zone Location

Four major process metallurgy-physical metallurgy relationships were derived from the comprehensive global hot ductility study. Based upon the process metallurgy data supplied by the industrial partners, it was determined that the hot ductility, EACLG and stress strain behavior are closely related to; 1) deleterious effect of very high tap temperatures, 2) the positive effect of controlled superheat, 3) positive effect of maximization of casting speed and 4) deleterious effect of high secondary cool zone temperatures [17]. A chemistry comparison of different combinations of process metallurgy parameters to the hot ductility data and propensity for cracking showed it to be more related to the carbon content than the microalloy composition.

Addition of a single- or multi-microalloy chemistry affects the hot ductility behavior in a laboratory test and hence, based on the literature, the perceived crack propensity. Hot ductility behavior of microalloy steels results in excellent surface quality at low %RA and crack-free slab quality. The incongruence of %RA and propensity for cracking and poor hot ductility behavior is validated. Strain energy is recommended to better predict cracking propensity.

8. Conclusions

The analysis of the stress strain behavior and strain energy and %RA data is related to solidification and the sub-surface EACLG transition zone location. The steelmaking and continuous casting process metallurgy variables such as superheat, casting speed, primary and secondary cooling directly influence solidification and hence, the resultant grain size distribution. The hot ductility behavior was studied in relation to the chemical composition, process metallurgy variables and hot ductility behavior for a variety of microalloyed and non-microalloyed steel chemistries. All samples were obtained from industrial operations. Percent

RA has been the traditional assessment tool to characterize the hot ductility behavior and potential propensity for cracking. This study introduces the strain energy as an alternative measure for hot ductility behavior assessment and exhibits a stronger correlation coefficient to strain at the ultimate tensile strength than %RA exhibits. The literature quotes 40% RA minimum for Nb-bearing steels when in fact as low as 10% minimum RA is more than sufficient to assure crack-free casting based upon the extensive testing, operational parameter review and analysis performed in this study. Strain energy has been introduced to evaluate hot ductility behavior. The strain energy is a better measure of hot ductility behavior than %RA. The research explores that there is considerable value in the evaluation of the hot stress and strain curves, process metallurgy parameters and their relationship to slab and billet continuous cast quality instead of just basing hot ductility on simple %RA measurement.

References

[1] C. Ouchi and A. Matsumoto, "Hot Ductility in Nb-Bearing High Strength Low-Alloy Steels," Transactions ISIJ, Vol. 22, 1982, pp. 181-189

[2] B. Mintz and D. N. Crowther, "Hot Ductility of Steels and Its Relationship to the Problem of Transverse Cracking in Continuous Casting," International Materials Reviews, Vol. 55, No. 2, 2010, pp. 168-196

[3] W. R. I. a. A. Perkins, Int. Conf. Organized by the Metals Society, London and L'Institut the Recherches de la Sidérurgie Francaise (IRSID), Biarritz, (1977), p.330

[4] J. K. Brimacombe, F. Weinberg and E. B. Hawbolt, "Continuous Casting Heat Flow, Solidification and Crack Formation," 2, I. S. S. of AIME, ed. by BookCrafters, Chelsea, U.S.A., (1984), p.215

[5] S. K. Mishra Pathak, S. Das and S. Ranganthan, Mater. Sci. Eng. A, **A323** (2002), p.285

[6] J. Konishi, M. Militzer, J. K. Brimancombe and I. V. Samarasekera, Metall. Mater. Trans. B, 33B (2002), p.413

[7] C. Cicutti and R. Boerl, Steel Res. Int., **77** (2006), p.194

[8] D. M. Stefanescu, ISIJ Int., 46 (2006), p.786

[9] J. Ruiz Mondragon, M. Herrera Trejo, M. Castro Roman and H. Solist, "Description of the Hypo-peritectic Steel Solidification under Continuous Cooling and Crack Susceptibility," ISIJ Int., 48 (2008), pp.454-460

[10] R.J. Gray, A. Perkins and B. Walker: Sheffield International Conference on Solidification and Casting, The Metals Soc., London, (1977), p.967

[11] B. Mintz, "Importance of Ar3 Temperature in Controlling Ductility and Width of Hot Ductility Trough in Steels and its Relationship to Transverse Cracking," Materials Science Technology, Vol. 12, 1996, pp.132 – 138

[12] P. Lukas, L. Kunz, Mater. Sci. Eng. 85 (1987), p.67

[13] M.A. Meyers, E. Ashworth, Philos. Mag. A: Phys. Condens. Matter Struct. Defects Mech. Prop. 46 (1982), p.737

[14] K.-S. Cheong, E.P. Busso, J. Mech. Phys. Solids 54 (2006) p.671

[15] Y. Guilhem, S. Basseville, F. Curtit, J.M. Stephan, G. Cailletaud, Int. J. Fatigue 32 (2010), p.1748

[16] Z.F. Zhang, Z.G. Wang, Progr. Mater. Sci. 53 (2008), p.1025

[17] This work was conducted by S. G. Jansto in his Ph.D. dissertation at Illinois Institute of Technology, Materials Science & Engineering Department, Chicago, USA and completed in December 2013