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Solidification and Strain Energy Relationship during the Continuous Casting of Microalloyed Advanced High Strength Steels

Steven G. Jansto, Ph.D, MBA[1]

[1]*CBMM North America, Materials Science and Engineering, 1000 Old Pond Road Pittsburgh, PA, 15017, USA*

Microalloyed steels are an important product within the automotive, energy, pipeline and structural segments. Slab 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 superheat, mould level fluctuation, heat transfer, equiaxed chill zone depth and other process performance parameters will directly influence solidification behavior and hence the surface and internal quality of the steel strand. These melting and casting parameters require proper control regardless of the microalloy composition. 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 microalloyed steels. Strain energy measured from industrial heats is a better measure of the hot ductility behavior than %RA area to better explain the incongruence between %RA prediction and the propensity for slab cracking in microalloyed steels.

Keywords: hot ductility, microalloys, Strain Energy, stress-strain behaviour, unbending

1. Introduction

1.1 Background

There are several published papers based upon the relevance of the traditional 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[1,2,3,4)]. 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 and process metallurgy parameters of the actural steelmaking operations are rarely correlated to the hot ductility behavior and resulltant 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. 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 and strain gradients in the caster. In addition, most hot ductility studies involve laboratory produced heats whereas this research is based solely upon industrial produced samples with an emphasis on process parameters.

1.2 Research Purpose

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. 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 measurment. This research explores different carbon equivalent microalloyed steels which reportedly exhibit inherently lower hot ductility, as measured by percent reduction in area at elevated temperature. Yet, at these low %RA values, these steels still demonstrate sufficient ductility to satisfactorily meet the unbending stress and strain gradients experienced in actual industrial caster operations and were then successfully hot rolled into prime quality sheets and plates.

1.3 Industrial Sample Family

The sample family in this study 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 global steel producers observed 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. The area of study involves the unbending section of the caster in the temperature range of 700 to 950°C. A schematic diagram of this region is shown below in Figure 1.

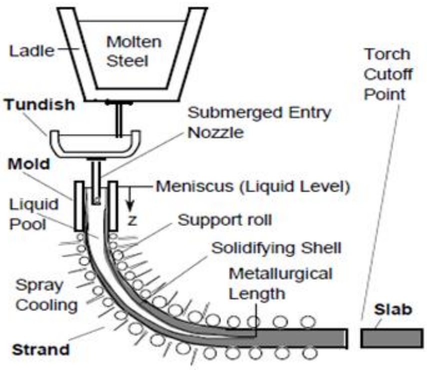

Fig. 1 Detailed schematic of thick slab continuous caster[5)]

Since the typical temperature through the unbending section of the caster is between 700 to 950°C, most of the 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. This strain rate simulates the strain rates induced within the unbending section of industrial casters at typical casting speeds for microalloyed steels.

2. Materials and Methods

2.1 Heating and cooling schedule

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 which 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). Figure 2 below schematically presents an example of the heating and cooling schedule for an 800°C test temperature with a 60°K per minute cooling rate to the test temperature or 800°C in this example.

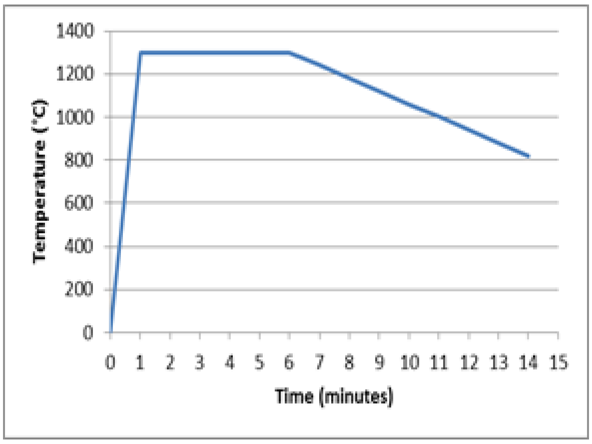

Fig. 2 Heating and cooling schedule for hot tensile test

The strain rates for all of the tests simulated the actual operational strain rate experienced at the unbending section of the casters' who provided samples and process metallurgy data for this global study. The two strain rates employed were between 0.001 and 0.0001 mm/mm/second which is the typical strain rate range globally. The raw data output of force, dynamic gauge measurements, stress and strain were converted into a stress strain curve for each sample. The fracture surface area was measured using a Mitutoyo micrometer and recorded as %RA of sample fracture surfaces.

2.2 Sample Location

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, centerline samples hot ductility behavior would be affected by segregation versus surface samples or sub-surface samples which might exhibit an equiaxed or mixed grain macrostructure. In this research work, the intent is to determine the hot ductility behavior subsurface at or near the transition in grain size from the equiaxed chill zone to the columnar grain zone. This zone represents a variable grain size due to the transition from equiaxed to columnar grains and a high residual strain region exists due to the mixed grain microstructure. Upon solidification, the equiaxed chill zone is usually between 10 to 25mm in thickness depending upon the slab thickness being cast, casting speed, primary cooling rate and the associated heat transfer. Figure 3 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.

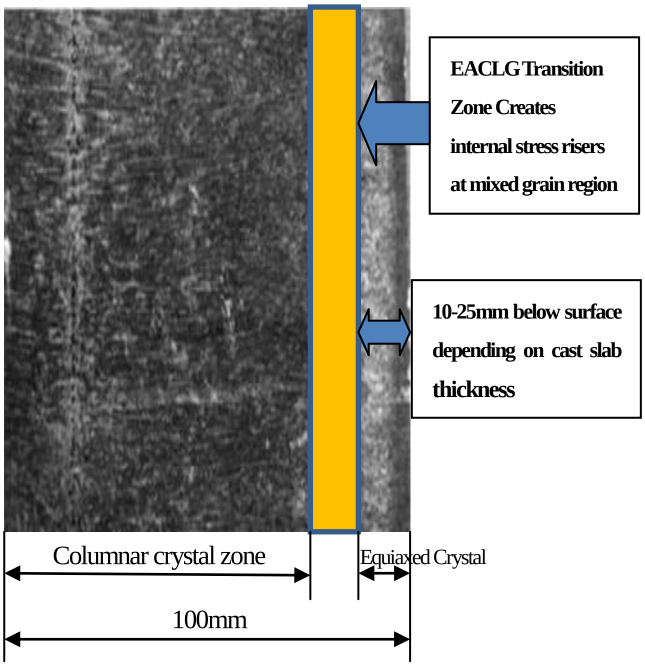

Fig. 3 Equiaxed and columnar zone macrograph

Samples were extracted from the cast slabs at the 20mm to the 80mm depth below the surface. The objective is to capture the Equiaxed-Columnar-Grain (EACLG) transition zone[6] which has higher internal residual strain due to the mixed grain feature of this subsurface region. The intent is to measure the hot ductility behavior form the weakest zone in the slab. For example, since most slab cracks initiate sub-surface and then propagate to the surface forming transverse cracks, the mechanical strength of the sub-surface transition zone should be measured. Therefore, samples were saw-cut from the full size master slab to minimize any distortion that may result from the torch cutting which would also change the cast slab microstructure and grain size. Figure 4 illustrates this unique subsurface sample location for the hot ductility tensile tests performed in this study to capture the sub-surface weak EACLG transition zone.

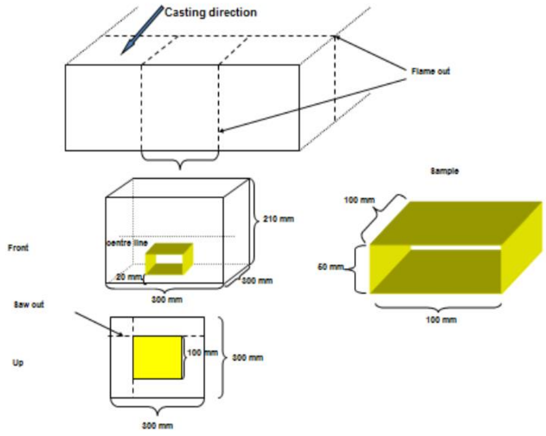

Fig. 4 Continuous cast sample location and orientation

2.3 Samples Composition

A variety of slab samples were obtained from industrial continuous casters. The microalloy compositions tested are shown in Table 1 and range from 0.045% to 0.253%C at various Nb, V, and/or Ti compositions. Operational data was also obtained for each slab sample. The data included casting speed, superheat, primary and secondary cooling parameters, oscillation frequency and stroke.

2.4 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 (EACLG) from equiaxed grains to the initiation of the columnar grains and 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.

Table 1 Industrial sample compositions

ID	C	Mn	Si	Nb	V	Ti	Mo	Cr	Cu	Ni	Al	S	P	N
1A	.158	1.45	.454	.041	.009	.004	.004	.048	.019	.046	.033	.002	.013	.0058
2A	.154	1.45	.455	.042	.009	.005	.006	.053	.027	.050	.033	.001	.014	.0027
3B	.074	1.55	.209	.050	.073	.019	.005	.046	.035	.049	.035	.002	.009	.0040
4C	.132	1.57	.260	.036	.079	.031	.005	.046	.015	.041	.035	.002	.008	.0058
5D	.411	1.68	.210	.002	.090	.017	.004	.053	.024	.046	.033	.007	.013	.0061
6E	.141	1.39	.390	.040	.078	.009	.006	.047	.026	.045	.029	.004	.011	.0062
7F	.142	0.61	.640	.002	.007	.005	.497	1.41	.016	.059	.039	.001	.008	.0083
8G	.253	1.05	.503	.002	.008	.028	.184	.387	.016	.369	.044	.002	.009	.0052
9H	.072	1.49	.250	.036	.008	.015	.004	.044	.142	.382	.036	.002	.009	.0056
10I	.081	0.99	.205	.002	.010	.028	.006	1.05	.022	.063	.036	.004	.010	.0047
11J	.072	1.41	.189	.023	.010	.014	.007	.053	.023	.051	.035	.005	.011	.0051
12K	.147	1.40	.377	.010	.009	.005	.007	.067	.033	.072	.039	.002	.011	.0041
13L	.045	1.90	.179	.084	.013	.098	.006	.042	.045	.051	.026	.002	.008	.0063

3. Results and Discussion

3.1 Hot tensile tests

The strain rates for all of the hot tensile 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. Evaluation of the percent reduction in area and the stress strain curves were made. The connection of a minimum % RA based upon the Gleeble test and propensity for cracking in the unbending section was then introduced by Mintz in a 1996 paper[7]. Within this body of research, it was established that a 40% minimum reduction in area as measured by a hot tensile test is the criterion to assure of crack-free casting of Nb-bearing steels during the continuous casting process. Extensive review of the literature and (private communication in the industry) was performed to further determine the origin of the 40% minimum RA requirement to prevent transverse cracking in

Nb-bearing steels, as it was not justified in the Mintz work. Their conclusion links the control of the composition and alteration of the precipitation process through the minimization or elimination of those elements that deepen or widened the hot ductility trough. Yet, no metallurgical and/or mechanical engineering derivation of the minimum required 40%RA was presented with supporting data to justify this minimum %RA. The implications of the overstated %RA target affect some alloy designers in reducing or eliminating the use of Nb in some steels. The problems then evolved that without Nb in many of these high strength plate, sheet and bar applications, mechanical properties were sacrificed. Specifically, toughness, fatigue, bendability and formability were deleteriously affected.

The traditional %RA data was generated for all of the industrial samples and Figure 5 is an example.

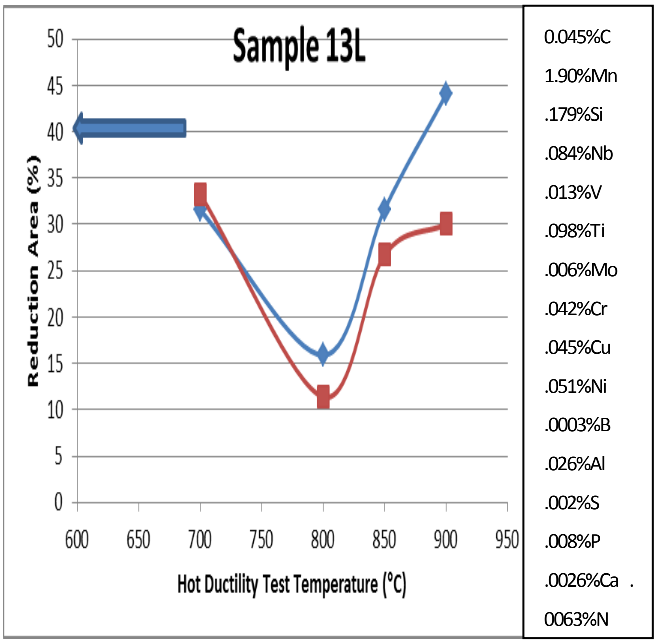

Fig. 5 Traditional %RA hot tensile data

Each microalloy has a purpose to serve. With proper melting and casting parameters, these microalloy compositions are well within the capability of producing crack-free slabs regardless of the individual microalloy, the combination of microalloys and the carbon equivalent of the grade even at as low as 10%RA, yet published literature quoted 40% minimum %RA[7] to assure crack-free casting of Nb bearing heats. Due to this lack of correlation between %RA from laboratory generated heat samples and actual performance in an industrial slab or bloom caster, it was decided to compare strain energy as a better measure for prediction of the hot ductility behavior.

In addition to the traditional %RA and temperature measurement, the raw data output of force, dynamic gauge measurements, stress and strain were converted into a stress strain curve for each sample. (See Figure 6 as an example.)

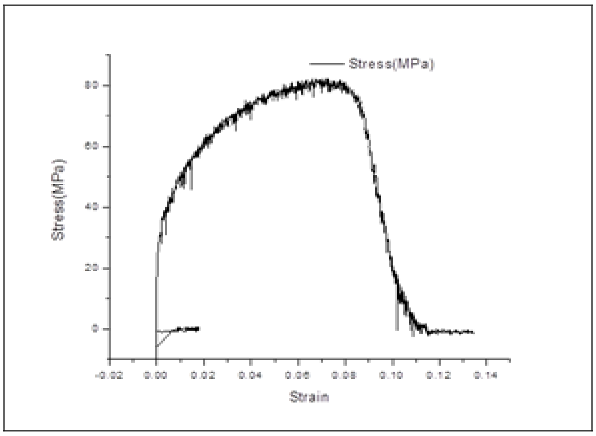

Fig. 6 Stress-strain curve for sample 1A at 800°C and 0.0001strain rate

3.2 Strain Energy

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 (Equation 1) is shown by:

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

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. Over 150 samples were tested, which highlights the behavior for four families of carbon ranges at very low carbon (<0.045%C), low carbon (0.050-0.090%C), peritectic carbon (0.100-0.165%C), medium carbon and high carbon.

3.3 Stress Strain Curve and Percent RA Correlation Results

The steels tested in this study exhibited a range of %RA data that were considerably lower than the published 40% minimum %RA required for crack-free casting of Nb-bearing steels. Yet, these steels did not exhibit cracks. Thus, the strain energy (SE) has been introduced to assist in ascertaining the hot ductility behavior of steels. It is postulated that the stress strain curve is a more accurate measure of a given steel's hot ductility behavior than a simple measurement of the %RA. In order to test this postulation, all of the %RA and strain energy data was plotted against ultimate tensile strength and strain at ultimate tensile strength. Figures 7 and 8 compare the strain energy and %RA as a function of the strain at the ultimate tensile strength.

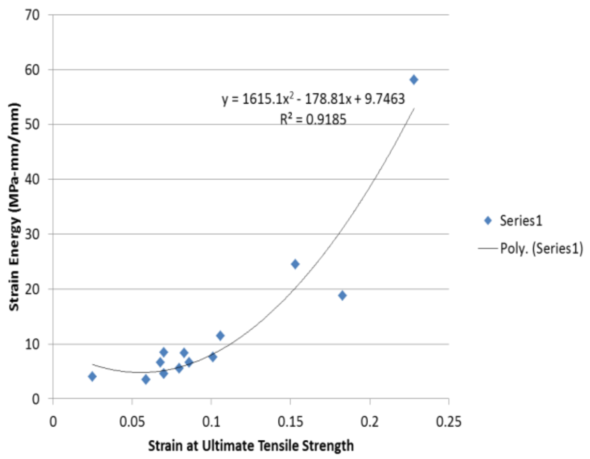

Fig. 7 Strain energy and strain at ultimate tensile strength[8)]

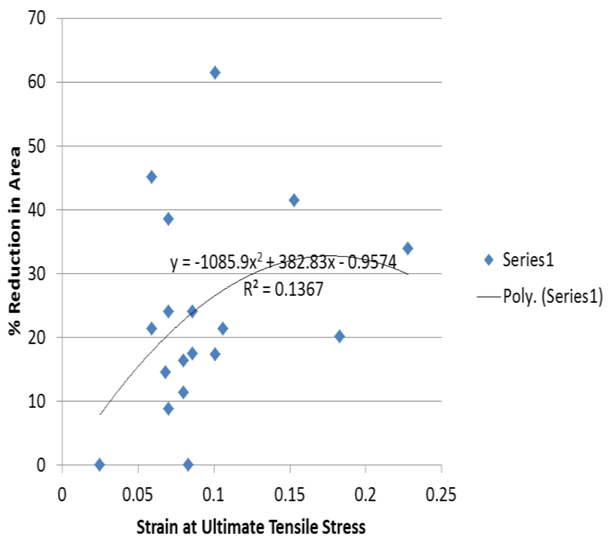

Fig. 8 %RA and strain at ultimate tensile strength[8)]

A strong R^2 of 0.906 was determined between the strain energy and strain at the ultimate tensile strength and only 0.1367 R^2 between the %RA and the strain at UTS as shown in Figure 7 and 8. The key factor affecting the subsurface crack propagation at the EACLZ will be the tolerable strain at the UTS. Additional investigation is suggested for future research work to further study the strain energy relationship and hot ductility behavior. As a result of the higher correlation for both the ultimate tensile strength and the strain, it is proposed that the strain energy be defined as the preferred measure of the hot ductility characterization for different microalloy compositions. Future researchers are encouraged to report strain energy data when performing hot ductility tensile tests at temperature. Hence, a global strain energy database should be compiled in order to further expand. Reasons for the poor strain correlation with %RA is related to process metallurgical factors and solidification behavior which are typically not considered in hot tensile testing and %RA determination. A strong R^2 of 0.906 was determined between the strain energy and the ultimate tensile strength (UTS) and R^2 of 0.919 for the strain at the UTS.

3.3 Process Metallurgy Results

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 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[8)].. 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.

The addition of a single- or multi-microalloy chemistry will affect the hot ductility behavior in a laboratory test and hence, based on the literature, the perceived crack propensity. However, the hot ductility performance in actual practice exhibits a contrary result. The hot ductility behavior of these microalloy steels result in excellent surface quality at low %RA and crack-free slab quality. The incongruence of the %RA and propensity for cracking and poor hot ductility behavior is validated.

4. Conclusions

The conclusion indicates that a low %RA does not necessarily equate to the incidence of transverse cracking under proper processing conditions. The actual relevance of the %RA criterion for any chemistry steel should be met with skepticism when designing microalloy grades. 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 behaviors and potential propensity for cracking. This study introduces the strain energy as a better measure for assessing hot ductility behavior and exhibits a stronger correlation coefficient to strain at ultimate tensile strength (UTS) than %RA.The application of laboratory-generated heat data does not accurately emulate the hot ductility behavior of samples obtained from industrial casters. This research determined that the minimum required %RA for crack-free casting is inaccurate and significantly overstates the %RA required for crack-free castability. 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 according to actual operational results and data. In conclusion, strain energy is a better measure of hot ductility behavior than %RA. There is considerable value in the evaluation of the hot stress and strain curves, process metallurgy parameters and their relationship to slab quality.

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