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STRAIN ENERGY CONSIDERATIONS FOR THE CONTINUOUS CASTING OF HIGH QUALITY NB-TI-V MICROALLOYED STEELS

Abstract

Much has been published about the traditional hot ductility trough associated with higher carbon equivalent steels with and without microalloy additions of Nb, V and/or Ti. Over 300 million tons of high-quality Nb, V and Ti-bearing microalloyed steels were produced globally in 2013. Although microalloyed steels are reported to exhibit lower hot ductility, it is based upon the measured percent reduction in area (%RA) from a hot tensile test. However, despite lower %RA, these steels exhibit sufficient ductility to satisfactorily overcome the unbending stress and strain gradients existing in the straightening section of most casters. This condition is validated by the high level of slab quality performance observed in the slab inspection yard. Therefore, a richer understanding of the slab resistant cracking mechanism is advocated. This study introduces the concept of correlation of the stress-strain behavior and effective strain energy of different microalloy chemistries as it relates to the steelmaking and caster operational parameters and resultant slab quality. This global microalloy research study is based upon samples obtained from industrial casting operations. The associated steelmaking and caster process parameters are related as well. The inter-relationship between steelmaking and caster process metallurgy parameters and resultant hot ductility stress-strain behavior and strain energy are presented.

Keywords

Caster operational variables, Strain energy, Stress-strain behavior

1. Introduction

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 focus 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

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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. 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.

2. Background

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.

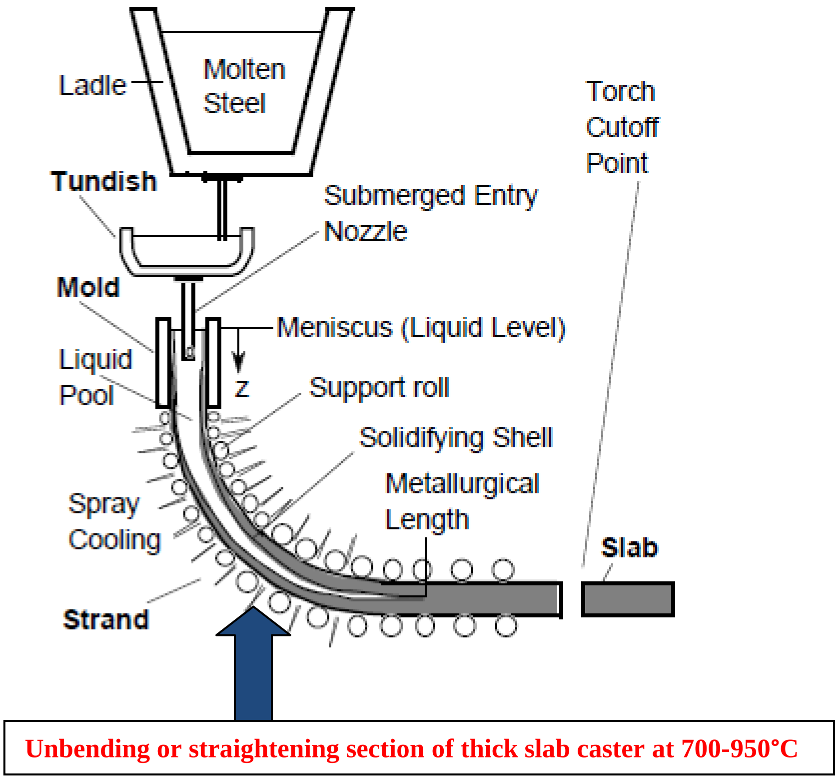

Figure 1. Detailed Schematic of Thick Slab Continuous Caster [5]

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. Figure 2 illustrates the %RA at different strain rates for Nb microalloyed steels.

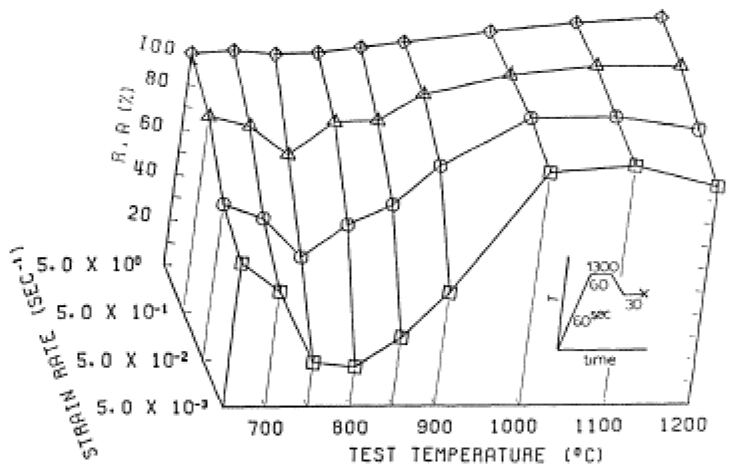

Figure 2. Dependence of Ductility on the Strain Rate and Test Temperature for the Nb-Low Carbon Steel [6]

Note that 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 generating a 0.0001 to 0.0001 mm/mm/sec strain rate.

The connection of a minimum % RA based upon the Gleeble test and propensity for cracking in the unbending section was introduced by Mintz in a 1996 paper [7]. Extensive review of the literature and (private communication in the industry) was performed to determine the origin of the 40% minimum RA requirement to prevent transverse cracking in Nb-bearing steels. The conclusion clearly 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 mechanical engineering derivation of the minimum required %RA was presented to avoid transverse cracking.

Based upon this reported minimum 40%RA 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 minimum %RA casting criterion. Yet based upon actual operational experience and this hot ductility study, %RAs as low as 10% will result in crack-free casting of Nb-bearing steels at industrial casters around the world.

3. Mechanical Hot Ductility Test Program

Hot tensile tests were performed on a Gleeble 3500 thermomechanical system. The Gleeble 3500 has a fully integrated digital closed loop control thermal and mechanical testing system. The equipment is supported by Windows based computer software, combined with a processor providing an interface to create, run and analyze data from hot ductility tests and physical simulation programs. 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 which simulate the actual casting conditions from the industrial casters who 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 3 below schematically presents the heating and cooling schedule for a 800°C test temperature example.

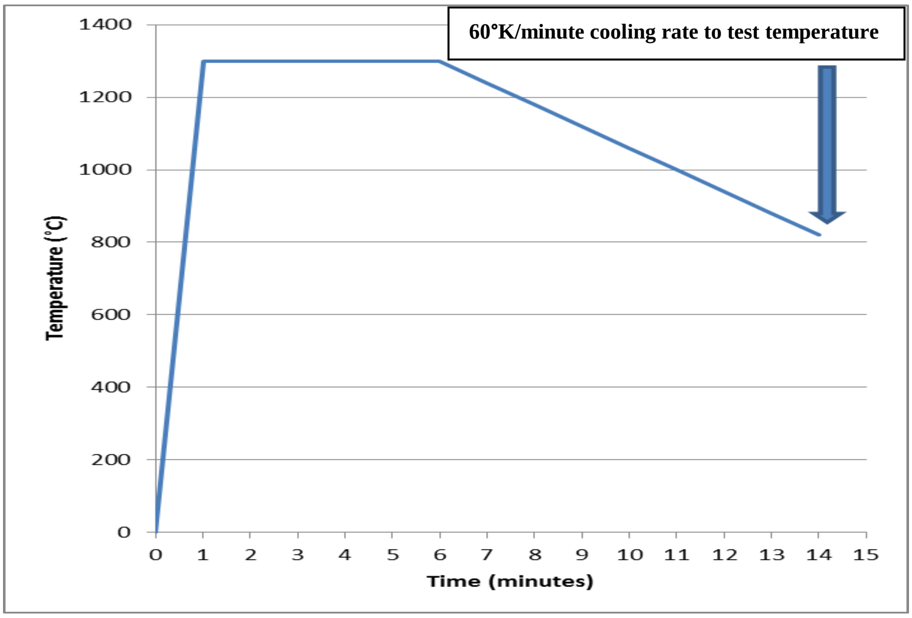

Figure 3. Heating & Cooling Schedule Example for 800°C Test at Two Strain Rates (0.001 mm/mm/sec and 0.0001mm/mm/sec)

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. (See Figure 4 as an example.)

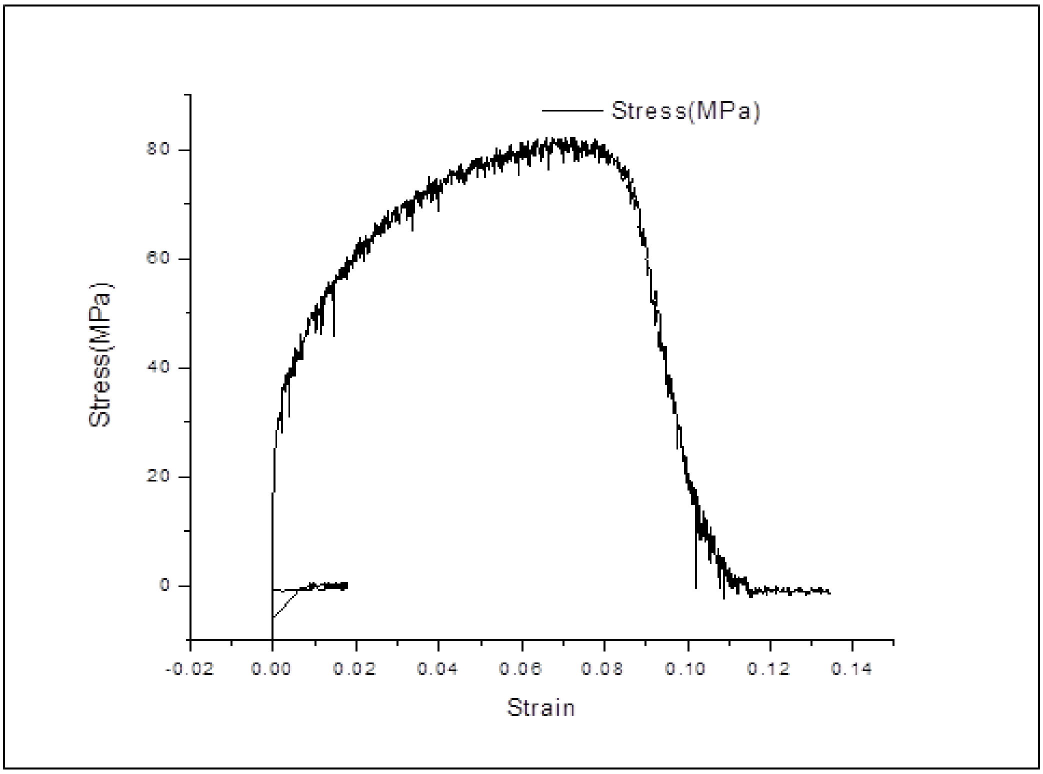

Figure 4. Conversion to Stress Strain Curve (sample 1a at 800°C and 0.0001 strain rate)

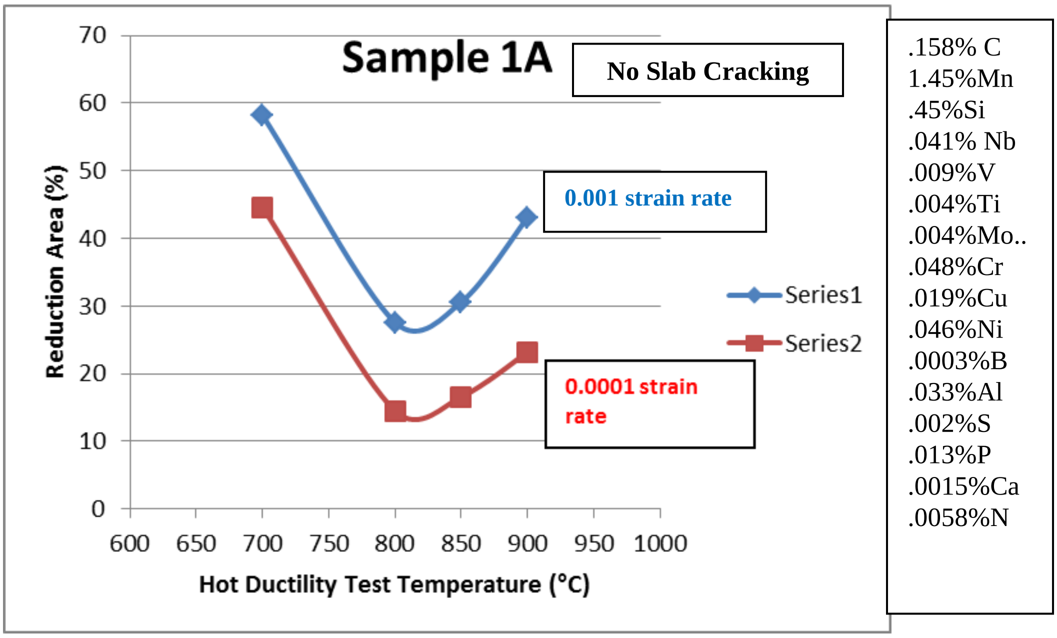

Figure 5. % RA versus Test Temperature

Note that Sample 1A and other Nb-only, Nb+V or Nb+V+Ti tested showed no slab cracking. Gleeble tests exhibited %RAs as low as 10-15% with no slab cracking. Thus, this study identifies clearly that sufficient hot ductility exists in Nb and other Nb-microalloyed steels to accommodate the induced strains within the unbending section of casters.

The measure of %RA to assess the probability of crack formation during casting is highly inaccurate. This work suggests that the %RA test as an assessment tool to predict cracking or not is an invalid tool. These crack-free cast slab conclusions are based upon the extensive testing and analysis performed in this study and detailed evaluation of the stress-strain curves. The calculated strain energy is studied as an alternative tool to better capture the hot ductility behaviour of these microalloyed crack-free cast steels.

4. Strain Energy Calculations

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:

$$U^* = \frac{1}{V}\int P\,dL = \int_0^L \frac{P}{A_0}\frac{dL}{L_0} = \int_0^\epsilon \sigma\,d\epsilon \qquad [1]$$

Strain energy (SE) was calculated for the microalloy compositions tested through the integration of the area under the stress strain curves. The calculated strain energy data is listed below in Table 1 as well as the %RA for comparison. The associated compositions are shown in Table 2. Again, it is extremely important to note that none of these slabs exhibited slab cracking.

Table 1. % Reduction in Area and Strain Energy at 800°C

Sample*	**Casting Speed (m/min)**	**SE at 800°C 0.001**	**SE at 800°C 0.0001**	Δ_{SE}	**%RA at 800°C 0.001**	**%RA at 800°C 0.0001**	Δ_{RA}
1A	1.16	19.381	6.663	12.718	27.6	14.5	13.1
2A	1.16		11.466		43.3	21.4	21.9
3B	1.22	41.269	22.931	18.338	48.9	33.9	15.0
4C	1.16	58.142	44.564	13.688	68.1	58.0	10.1
5D	1.35	46.489			70.7		
6E	1.16	27.291	8.375	18.916	38.0	20.1	17.9
7F	1.17	21.927	12.742	9.185	46.9	38.5	8.4
8G	1.16	37.986			85.2		
9H	0.89	38.886			47.9		
10I	1.35	52.427	24.554	27.873	73.5	61.4	12.1
11J	1.09	40.695	18.760	21.935	59.2	45.1	14.1
12K	1.16	23.372	8.404	14.968	39.4	24.1	15.3
13L	1.18	12.270	4.094	8.176	15.0	11.4	3.6

Table 2. 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

A comprehensive analysis of the stress strain curve data and correlation analysis was performed between the strain energy and ultimate tensile strength. A strong R^2 0f 0.906 was recorded when correlating the strain energy versus the ultimate tensile strength as shown below in Figure 6.

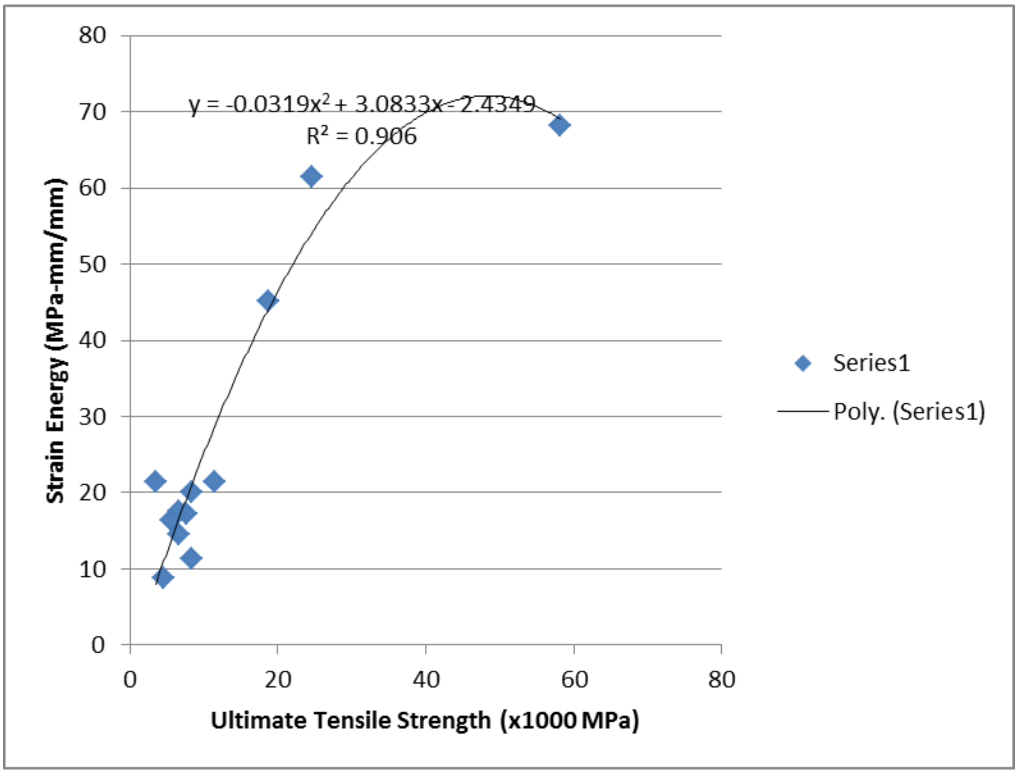

Figure 6. Strain Energy versus Ultimate Tensile Strength at 800°C

A significant result of the correlation analysis shows a very low R^2 for the %RA versus the strain at the ultimate tensile strength. However, a strong R^2 is apparent for the strain energy versus strain as shown below in Table 3.

Table 3. Correlation Coefficient R^2 Comparison of Strain Energy and %RA

	%Reduction in Area	Strain Energy
Ultimate Tensile Strength	.7276	.9060
Strain at Ultimate Tensile Strength	.1367	.9185

As a result of the higher correlation for both the ultimate tensile strength and the strain, it is proposed that the strain energy is a 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.

5. Process Metallurgy Factors

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. 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.

6. Conclusions

The analysis of the stress strain behavior and strain energy and %RA data has been related to the steelmaking and continuous casting process metallurgy principals. 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 a measure for hot ductility behavior assessment and exhibits a stronger correlation coefficient to strain than %RA.

The application of laboratory generated heat data does not completely emulate the hot ductility behavior of samples obtained from industrial casters. Consequently, 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 and analysis performed in this study.

Strain energy has been introduced to evaluate hot ductility behavior. It is concluded that 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 instead of just basing hot ductility on simple %RA measurement.

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