Hot Ductility Behavior and Slab Crack Performance of Microalloyed Steels During Continuous Casting

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Abstract This research shows that high carbon equivalent microalloyed steels which exhibit inherently lower hot ductility, through the hot tensile test as measured by percent reduction in area (%RA), still exhibit sufficient ductility to satisfactorily meet the unbending stress and strain gradients existing in the straightening section of most industrial casters. Operational results indicate only 10%~15%RA as measured by the hot tensile test, exhibits superior ductility and no cracks are generated through the unbending section of the caster. The published %RA data over the past several years has grossly overstated the minimum ductility required for crack-free casting of Nb-bearing steels by two to threefold, as well as other microalloyed steel grades. The research study clearly connects the relationship between the steelmaking and caster operation and carbon content as the primary drivers of the hot ductility behavior and resultant slab quality. The overall composition is not the primary driver. However, the carbon level of the steel and solidification considerations are the primary drivers affecting surface quality such as slab cracking. The location of the equiaxed-columnar grain transition zone below the surfacesignificantly affects the sub-surface residual strain gradient. This paper also introduces strain energy as a better measure of the hot ductility behavior than %RA which better explains the incongruence between %RA and propensity for slab cracking in microalloyed steels. This research is based solely upon industrial produced heats with an emphasis on the effect of process parameters on hot ductility behavior and successful production of crack-free slabs.

Key words continuous casting, equiaxed-columnar grain transition zone, hot ductility

1 Introduction

The level of surface and internal defects impart a direct impact on the overall steel production operating costs, internal and external cost of quality and delivery performance. Niobium (Nb), Titanium (Ti), Vanadium (V) and high Carbon (C) equivalent, high strength microalloyed steel grades are reported as prone to continuous casting surface and crack defects depending upon specific metallurgical factors[1].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[2~5]. This early research focus by others has primarily studied the chemistry and optimal composition suggested in order to increase the %RA during the unbending of the continuous cast slab, thereby raising the ductility trough. These conclusions were based upon laboratory cast heats as well which does not emulate the actual cast structure. Again, as recent as 2010, the focus centered on chemistry and %RA[6]. Although the emphasis on chemistry has been well studied, the steelmaking 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 hot ductility studies involve laboratory produced heats whereas this research is based solely upon industrial produced samples with an emphasis on process parameters. This research explores different carbon equivalent microalloyed steels which reportedly exhibit inherently lower hot ductility, as measured by %RA at elevated temperature. At quite low %RA values measured in this study, 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. The traditional practice of measuring potential propensity for cracking and low %RA values is suspect and incongruent with actual operational results.

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 that 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 deeper troughs with microalloyed steels are generally related to the reduced hot ductility (percent reduction in area of 20% to30%) 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[7].

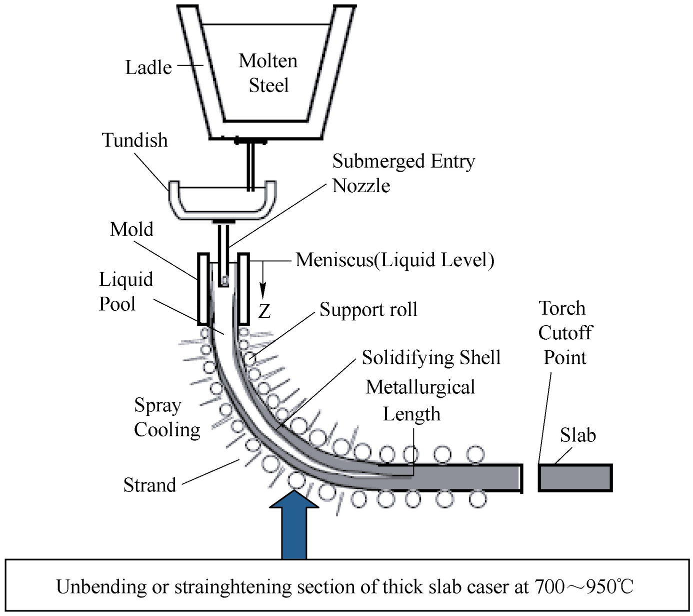

Fig.1 Detailed schematic of thick slab continuous caster

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 Fig. 1.

Industrial Slab Sample Compositions. A variety of slab samples were obtained from industrial continuous casters. A key objective of this research is to determine the %RA for industrial cast slabs which exhibit no cracks or surface quality issues. Most previous research was performed on laboratory produced heats. This data is presented to establish a baseline for the industry. Process metallurgy data was recorded as well. 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.

Table 1 Industrial steel compositions

ID	C	Mn	Si	Nb	V	Ti	Mo	Cr	Cu	Ni	Al	S	P	N
1A	0.158	1.45	0.454	0.041	0.009	0.004	0.004	0.048	0.019	0.046	0.033	0.002	0.013	0.0058
2A	0.154	1.45	0.455	0.042	0.009	0.005	0.006	0.053	0.027	0.050	0.033	0.001	0.014	0.0027
3B	0.074	1.55	0.209	0.050	0.073	0.019	0.005	0.046	0.035	0.049	0.035	0.002	0.009	0.0040
4C	0.132	1.57	0.260	0.036	0.079	0.031	0.005	0.046	0.015	0.041	0.035	0.002	0.008	0.0058
5D	0.411	1.68	0.210	0.002	0.090	0.017	0.004	0.053	0.024	0.046	0.033	0.007	0.013	0.0061
6E	0.141	1.39	0.390	0.040	0.78	0.009	0.006	0.047	0.026	0.045	0.029	0.004	0.011	0.0062
7F	0.142	0.61	0.640	0.002	0.007	0.005	0.497	1.41	0.016	0.059	0.039	0.001	0.008	0.0083
8G	0.253	1.05	0.503	0.002	0.008	0.028	0.184	0.387	0.016	0.369	0.044	0.002	0.009	0.0052
9H	0.072	1.49	0.250	0.036	0.008	0.015	0.004	0.044	0.142	0.382	0.036	0.002	0.009	0.0056
10I	0.081	0.99	0.205	0.002	0.010	0.028	0.006	1.05	0.022	0.063	0.036	0.004	0.010	0.0047
11J	0.072	1.41	0.189	0.023	0.010	0.014	0.007	0.053	0.023	0.051	0.035	0.005	0.011	0.0051
12K	0.147	1.40	0.377	0.010	0.009	0.005	0.007	0.067	0.033	0.072	0.039	0.002	0.011	0.0041
13L	0.045	1.90	0.179	0.084	0.013	0.098	0.006	0.042	0.045	0.051	0.026	0.002	0.008	0.0063

3 Percent Reduction in Area at Temperature Results

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/s and held for 5 minutes. to assure that the microalloy precipitates went back into solution. The cooling rates are at 60K/min which simulate the actual casting conditions from the industrial casters who produced the steel samples.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).The %RA at temperature data for crack-free low carbon, peritectic and medium carbon produced steel slab compositions is compiled below in Table 2.

Table 2 Percent reduction in area results

Sample	700°C	800°C	850°C	900°C	950°C	Strain Rate
1A	58.2	27.6	30.6	43.1	NA	0.001
	44.6	14.5	16.6	23.2	NA	0.0001
2A	64.5	43.3	54.0	23.2	NA	0.001
	49.5	21.5	29.9	42.5	NA	0.0001
3B	66.3	48.9	67.2	68.8	NA	0.001
	NA	33.9	54.7	72.1	NA	0.0001
4C	73.0	NA	68.1	86.0	89.0	0.001
	64.1	NA	58.0	81.1	85.0	0.0001
5D	50.3	70.7	NA	91.7	90.9	0.001
	31.8	41.5	NA	82.9	85.9	0.0001
6E	61.4	38.0	53.8	57.4	NA	0.001
	43.9	20.1	27.4	36.2	NA	0.0001
7F	86.6	46.9	65.9	57.5	NA	0.001
	74.2	38.5	45.0	37.1	NA	0.0001
8G	73.2	85.2	93.2	91.3	NA	0.001
	NA	NA	NA	NA	NA	0.0001
9H	72.2	47.9	NA	75.7	86.7	0.001
	54.1	24.1	NA	55.1	NA	0.0001
10I	75.8	73.5	NA	94.2	95.6	0.001
	74.6	61.4	NA	92.5	93.9	0.0001
11J	58.7	59.2	NA	78.0	81.0	0.001
	75.6	45.1	NA	66.0	77.6	0.0001
12K	73.7	39.4	53.3	68.4	NA	0.001
	57.2	24.1	25.6	31.2	NA	0.0001
13L	31.6	15.9	31.6	44.0	NA	0.001
	33.3	11.4	26.7	30.0	NA	0.001

An example of the Gleeble hot ductility %RA test results from an industrial sample that was cast crack-free and hot rolled into prime product is illustrated in Fig.2.

The hot ductility behavior based on industrial samples showed crack-free casting of sample 13L.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[4] 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.

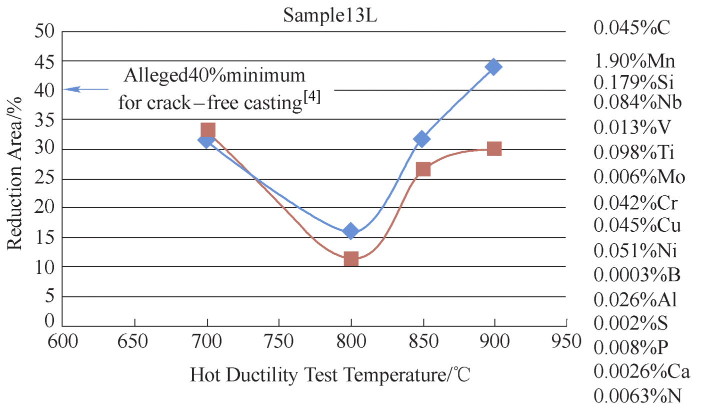

Fig. 2　Reduction in area versus test temperature for hot tensile test

Effect of carbon level on hot ductility. The carbon effect on hot ductility behavior and solidification has a far more profound effect on the propensity for cracking than the microalloying contents. The fundamental issue is the solidification phenomena and the thickness of the equiaxed chill zone in relation to the columnar zone during solidification in the upper segments of the caster. As a result of a significant difference in the heat transfer of the steel, especially in the peritectic region of 0.11% to 0.18%C, a significant decrease in %RA are measured. Singh and Blazek were the first to show that steels cast into a continuous casting machine slab mould exhibited a dip in the heat transfer for the solidifying shell to the mould at carbon contents of 0.10%~0.18%C[8]. Sugitani and Nakamura then showed quantitatively that the dip in heat transfer was due to the non-uniform shell formation in the CC mould[9]. The air gaps between the mould wall and the steel shell reduces the heat transfer, resulting in higher temperatures and thinner shells which leads to hot spots and then cracks. The steel melt initially solidifies in the CC-mold, a thin shell forms along the periphery of the mould near the meniscus. Then, the contraction upon solidification and subsequent cooling of the shell imposes hoop stress on the shell, which is the maximum at the center of the wide face of the shell. This uneven shell growth effect due to carbon content and its relationship to %RA is illustrated in Fig. 3 and the %RA versus C content is shown in Fig. 4.

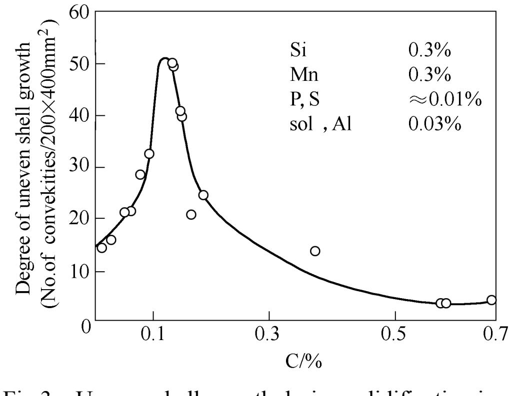

Fig.3　Uneven shell growth during solidification in mould[9]

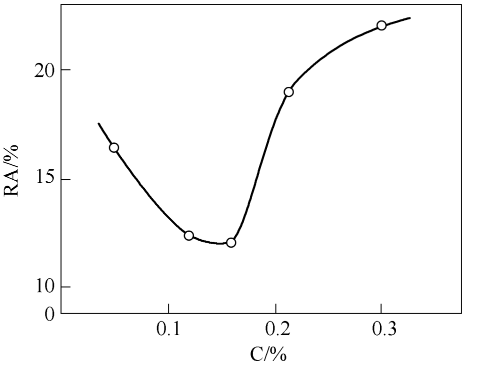

Fig.4　%RA and carbon content relationship[10]

The %RA was deduced from the grain size dependency for specimens that were reheated to 1300°C, deformed at 800 °C and at a strain rate of 0.83×10^{-3}/sec. In the tensile test after remelting using the Gleeble tensile machine, the ductility could not be evaluated accurately due to the shrinkage cavities that were formed. However, it was observed that the fracture surfaces were markedly influenced by the C content. Extensive intergranular fracture was recognized in the steels containing 0.11% and 0.13 % C with very coarse austenite grains compared with those in lower or higher C steels.

4　Strain Energy

This strain energy approach 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 has introduced the strain energy relation to hot ductility behavior and the related significant processing variables. Beyond the scope of this paper, strain energy results are reported by this author in previous work[11]. 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. A global strain energy database should be compiled in order to further expand the resource.

5 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 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. The application of laboratory generated heat data does not completely emulate the hot ductility behavior of samples obtained from industrial casters. Carbon contents, especially peritectic grades (in the range of 0.11-0.18%C), should be avoided.

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