Process Optimization and Product Metallurgy in Long Products

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The recent technological integration of both the process and physical metallurgical advancements of value-added niobium (Nb)-microalloyed long products has evolved into the development of low-cost, high-quality, low-manganese steels for long product end user requirements. This innovative metallurgical connection is validated by the market demand for improved quality and improved steel ductility, robustness and toughness in both the automotive special bar quality and construction steel sectors. The complementary refinement of the microstructural grain size through MicroNiobium additions and reduced manganese (Mn) levels in long products improves the robustness of the steel to better accommodate process metallurgy variations. Applications are evolving for both low- and high-strength structural long products as well as engineering bar grade long products.

The connection of process and physical metallurgy is evolving through the integration of research aimed at improving product quality. However, often the connection of the process metallurgical parameters is not typically reported, especially with industrial data.

Process and Product Metallurgy Synthesis

The process and physical metallurgy in conjunction with the materials science engineering connection is vital in understanding and properly executing the successful transfer from the laboratory to industrialization. This paper discusses the connections between the process metallurgy of production with the resultant mechanical properties and microstructure of the commercially produced merchant quality bar (MBQ), special bar quality (SBQ) and sections.

Often natural operational procedural variations occur within the process metallurgical steps of melting, casting, reheating and rolling. These process metallurgical aberrations and variations affect microstructure and steel quality, thereby creating an environment at times for unexpected mechanical property results. For example, during the continuous casting operation, control of superheat, mold level fluctuation, and proper primary and secondary cooling are the highest process metallurgy priorities. These parameters directly affect solidification, proper equiaxed columnar grain transition zone (EACLGZ), exceptional hot ductility, excellent surface quality and reduced chemical segregation. In the final hot-rolled product, the influence reheat temperature, finishing temperature, hot bed cooling and cooling rates directly affect the resultant microstructure in the hot-rolled steel. Practical experience has identified deleterious mixed microstructures across a given product section associated with improper thermal control.[1] For example, the inhomogeneity of overcooling near the edges and corners on the rolled steel bar can result in a martensitic microstructure. Conversely, more homogeneous cooling near the center of the bar width results in a pearlitic/bainitic microstructure. However, when the process metallurgy parameters such as temperature, mechanical metallurgy reduction schedule, cooling homogeneity,

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rhomboidity and shape are in the proper range of the upper and lower temperature control limits, there is a high probability that the mechanical property specifications are met and/or exceeded for the customer. Therefore, less process control variability will better correlate to the laboratory steel developmental results. Congruency of the industrial process increases the probability that proper microstructures support the desired mechanical properties. Within a continuous bar rolling operation, the industrial relevance of proper roughing mill, finishing mill and hot bed temperature is of paramount importance. Variations in the incoming temperature at each of these stages can result in missed finishing temperatures and hence, less than desirable properties. The root cause for temperature variations at these rolling mills is directly related to the reheat furnace operation, efficiency and performance (Combustion Metallurgy Approach, CMA®).

During the continuous casting of the billets, the minimization of surface and internal defects has a substantial impact on steel-producing operating costs, internal and external cost of quality, and delivery performance. A keen and thorough understanding of the continuous casting process metallurgy parameters for given carbon grades and the hot ductility behavior of these low-, medium- and high-carbon steel grades are essential to successfully melt and cast high-quality long product steels.

The recent metallurgical advancements in both carbon-manganese commodity as well as value-added microalloyed steels position the metallurgical community to incorporate an increased focus on this process and physical metallurgy synergy. Few papers are published that discuss this synergy and more research and development in this body of knowledge is required. One of the most recent major developments is the global shift to lower-carbon and leaner alloy compositions to improve steel product robustness, low-temperature toughness, less centerline and quarter-point segregation, improved fatigue, and improved weldability. For example, one recent development involves the application of niobium (MicroNiobium of 0.01–0.02%) even in lower-strength steels for both structural flat and long products, allowing for Mn reductions of as high as 40%.[2] Benefits are both economic and improved quality. Certainly in conventional higher-strength steel SBQ products, Nb additions account for the recrystallization and very-fine-grained microstructures.

Future Operational and Metallurgical Long Products Manufacturing Trends

Steel long products are differentiated into MBQ, SBQ and sections. MBQ steels are produced to specific sizes with wide chemical limits to meet a set of properties where the end use is non-critical. MBQ bars are typically produced from unconditioned billets. The bars typically have quite liberal tolerances. The surface and core defects are wide and not very well quantified. The end users of MBQ may perform operations such as mild bending, hot forming, punching and welding. The steel cleanliness quality standards for internal porosity, segregation, surface seams and grain size are very liberal. SBQ is a long product of significantly improved properties. The market driver is such that specific stress levels in the application can be met by the steel.[1,2] These long steel products are manufactured to meet difficult automotive, truck, forging and heavy equipment applications, to name a few. Fatigue fracture and strength of the steel are enhanced, which provides a higher level of consistency and integrity. To meet the desired level of performance, the chemical composition and cleanliness of the steel are critical to achieve the required mechanical properties. The alloy design and clean steel practices are crucial in achieving special bar quality and have a direct impact on the dynamic properties such as fatigue life of a component. The steel cleanliness required depends on the low levels of chemical segregation, good inclusion ratings, and minimal internal and surface defects.

A differentiation between the commodity, or MBQ, and SBQ operational and metallurgical developmental trends is presented. The current and future global trends for MBQ are focused on:

- Reduced carbon levels to improve product fabrication and welding performance.
- Reduced manganese levels to minimize segregation and surface quality problems.
- Reduced residual element levels to improve both internal and external cost of quality with incremental decrease in sulfur and phosphorus levels.
- Grain refinement–induced MicroNiobium addition to offset yield and tensile strength reduction due to carbon and manganese reduction.
- Increased end user demands for improved fabrication, formability and weldability for structural long products, including rebar, angles, flats and channels (especially in construction sector for buildings, bridges and infrastructure).
- Energy savings at the reheat furnace via CMA.

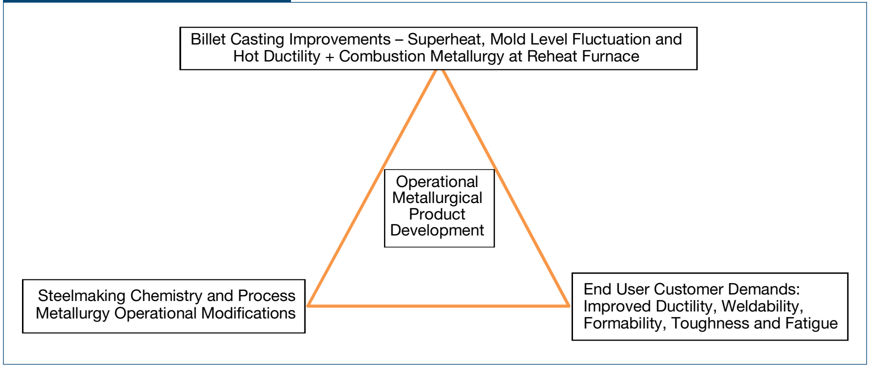
The current and future global trends for SBQ are focused on:

- Billet casting process operational and metallurgical improvements to improve homogeneity and both surface and internal quality (minimize cracking).

- Improved nitrogen control during steelmaking, especially in electric arc furnace operations.
- Scrap preparation and segregation practices to control residuals.
- Increased end user demands for improved fatigue, fracture toughness and reduced variability in yield-to-tensile ratio.
- Energy savings at reheat furnace via CMA.

The drivers for these operational, metallurgical and product development trends are shown in Fig. 1.

Figure 1



Long product manufacturing drivers.

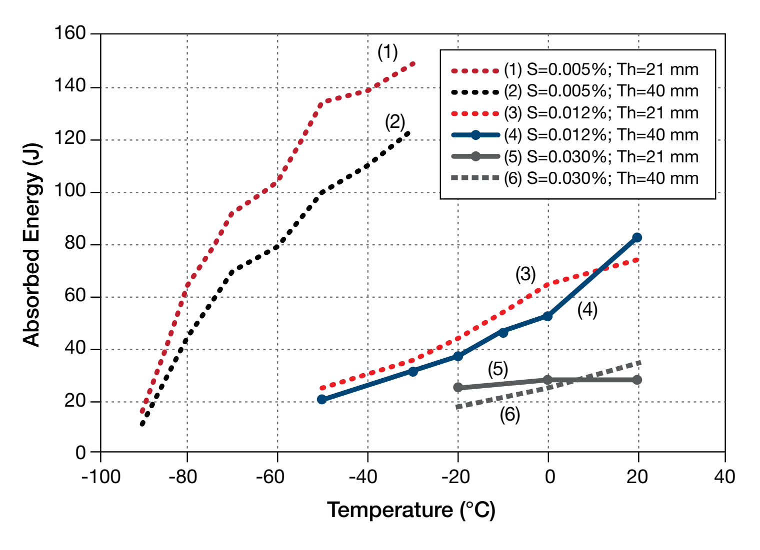
Long Products Steelmaking Future Trends

The electric arc or basic oxygen furnace long products steelmaking operation plays an important role in the production process. A differentiation is made here between long product commodity bar (MBQ) production compared to SBQ steelmaking. Steelmaking practices differ due to product quality specifications. Certainly, in the commodity grades supporting angles, channels and flats for construction, rebar and other structural products, allowed chemistry ranges are quite wide, with high residual levels. For example, sulfur and phosphorus levels may approach 0.025% and 0.035%, respectively. The future trends in some long product steelmaking shops involve both a reduction in sulfur and phosphorus levels (nearly a 50% reduction) as well as more restrictions on residuals. These reductions in sulfur and phosphorus result in reduced diverts and scrap, as well as increased rolling speeds and tons-per-hour production rates at the rolling mill. Certainly, these residual reductions enhance the quality and bar performance at the customer. The next step involves a reduction in carbon content to improve toughness, weldability and robustness even in low-strength grades such as S235, S275 and S355MPa construction grades. The benefits are not only improved quality at the customer, but a significant reduction in operational performance with reduced diverts, cobbles and increased production rates.

A second trend involves the grade consolidation to cross-apply structural plate and pipeline steel grade chemistries with the goal of reducing operating costs. Fewer grades lead to significant economies of scale at both the BOF/EAF shop and at the slab/billet caster. The implementation of clean steel low-sulfur–low-phosphorus practices is imperative if one intends to meet the future toughness and weldability demands of the evolving structural market. Through the application of clean steel, low-carbon low-alloy (LCLA), the reduction of finishing temperatures, and the incorporation of accelerated and/or controlled cooling can make significant reductions in operational costs.[3] The cross-application of these grade designs with proven process metallurgy practices is vitally important for the successful manufacture of both MBQ and high-quality, high-strength SBQ engineering grades. This cross-application approach derived from other product sectors such as automotive, plate and section (beam) products into long products can significantly benefit both MBQ and SBQ production rates and internal and external quality cost.

The beneficial effects of low sulfur and low phosphorus with strict nitrogen control significantly increase the probability of consistently producing high-quality structural steels exhibiting improved ductility, bendability, formability and resistance to cracking and toughness. This steelmaking operational change even applies to MBQ steel grades. A secondary internal steel mill benefit is that the lower sulfur and lower phosphorus steels improve both the castability and rollability of the steel, minimizing billet, beam and slab cracking. Improvements in the rollability of the steel through a reduction in the thermal resistance to deformation during rolling can also be achieved. These improvements translate to a minimum 10% reduction in operational cost per ton. Currently, there are very limited clean steelmaking practices applied to the production of commodity-type structural long products throughout the world. The process metallurgical cross-application approach from other products such as pipelines, beams and ship plate, to name a few, can be applied to long product production. For example, the toughness of S355 for construction plate applications at decreasing sulfur levels is presented as an example. Note that for each 50% reduction in sulfur, the Charpy impact strengths are improved at least three to four times. The paradigm shift here is

Figure 2



Sulfur effect on Charpy V toughness in transverse direction S355 grade.[4]

that this improvement is not only beneficial to the end user, but also to the hot rolling mill. This cross-application is illustrated in Fig. 2, which shows the toughness of S355 for construction plate applications at decreasing sulfur levels.

The strategy to lower the sulfur level is not only to accommodate the customer's need for improved toughness, but to also improve the rollability of the billet through the rolling mill. Currently, there are very limited clean steelmaking practices applied to the production commodity bar throughout the world. The cross-application of the process metallurgy practices applied to other products, such as pipelines, beams and ship plate, to name a few, can be applied to value-added structural long product bar production. Note that for each 50% reduction in sulfur, the Charpy impact values are improved at least three to four times. The benefits derived from finishing at low temperatures are well established. Again, some mills are restricted from rolling at these temperatures due to load constraints on the mechanical drives and motors.

Effect of Lower Carbon — Another cross-application of low-carbon plate production to long product bar will be considered. In the development of structural plate steels, a key consideration involves the low-carbon versus high-carbon approach and the effect of sulfur levels on the properties of the microalloyed structural product. Often overlooked is the positive financial impact of melting, casting and rolling a clean, low-residual, low-carbon steel on the overall cost of the operation.[9] The actual cost of steel production will be lower for S355 and in some cases lower for S235 and S275 grades, through the development of a carbon family less than 0.10%C with less than 0.50% residuals, less than 90 ppm N and less than 0.005%S. Coupling this strategy with a controlled lower finishing bar temperature rolling scheme will result in very fine ferrite grain sizes. Also, the weldability of these low-carbon steel grades is significantly improved by lowering the carbon equivalent by as much as 0.10. Typically, the influence of the base chemistry on the cold cracking susceptibility is a function of the carbon equivalent (CE) shown in Eq. 1.

$$CE + C + Mn/6 + (Cr+Mo+V)/5 + (Cu + Ni)/15 \qquad \text{(Eq. 1)}$$

In addition to improved weldability, the plate toughness is improved in a low-carbon (<0.08%C) approach versus a high-carbon approach (0.14–0.18%C). Similar benefits are seen in commodity bars as the metallurgical mechanisms are the same. Fig. 3 illustrates the improvement on toughness in the length direction in a low-carbon Nb composition versus a high-carbon composition.

In this metallurgical example, the 75-mm plate shows nearly triple the impact strength at –60°C as the carbon content is reduced from 0.14% to 0.07% with an addition of niobium. Hence, commercialization of the lower-carbon structural bar chemistry is preferred over the high-carbon chemistry because of better and more consistent mechanical properties, improved toughness, improved surface quality by avoiding the peritectic zone at the caster, and improved weldability. In addition, the improved surface quality assists in enhancing the adhesion of the epoxy coating for corrosion applications.

As a result of the grain refinement mechanism of niobium, higher yield strengths, improved weldability and improved fracture toughness can be achieved through a lowering of the carbon content. This allows the alloy designer the opportunity to specify lower-carbon-level steels to improve the toughness and weldability of the structure without sacrificing strength. An opportunity exists to study the niobium metallurgy and some of the grades applied to high-strength pipeline and advanced high-strength structural steel grades with lower carbon and microalloy systems for demanding applications such as seismic, low temperature, fire resistant, fatigue endurance limit and increased formability.

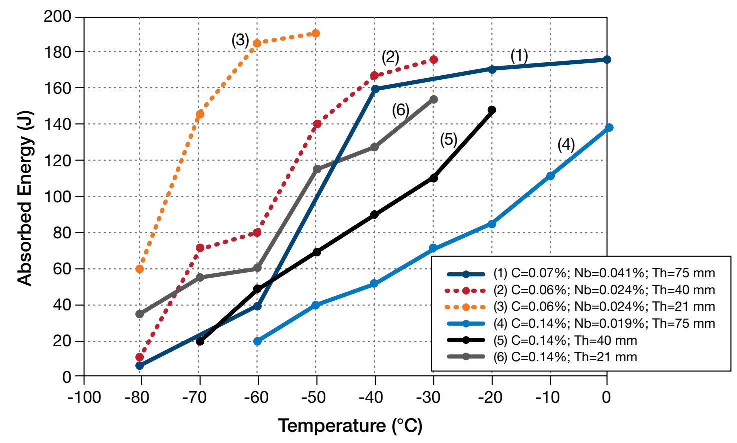
Within the MBQ sector, the judicious adjustment of carbon, sulfur and phosphorus levels should be evaluated. Many of the MBQ specifications offer a huge opportunity to tighten the internal specification, which will translate into significant operational cost reductions. These cost reductions better position the bar mill to successfully maintain excellent margins in a very competitive MBQ environment. Fig. 4 illustrates the significant effect of carbon on toughness, which is a significant benchmark to evaluate steel robustness during the hot roll mechanical metallurgy step of the long product production process.

Billet Reheating Process and Combustion Metallurgy

The reheat furnace process step has a profound effect on the rolling performance, final hot-rolled steel quality and mechanical property consistency during the production of both MBQ and SBQ hot-rolled steels. The uniformity of heating applied across the entire width and length of the slab or billet is critical in the achievement of customer properties regardless of the chemistry. The resultant ferrite grain size in the final hot-rolled product is significantly governed by the initial prior austenite grain size. Numerous reheat furnace process metallurgy and combustion parameters in actual operation affect mill productivity, microstructure, austenite grain size, scrap rate and diverts. This reheating step in the steelmaking process often receives low priority in the evaluation of product quality and mechanical property performance, especially the toughness through the plate thickness. Heat transfer conditions of radiation, convection and conduction affect furnace heating efficiency. In laboratory studies, the furnace heating step is typically quite uniform, resulting in a homogeneous and fine prior austenite grain size. During production, it is much more difficult to control the uniformity of heating and heat transfer consistency along the entire length and through the thickness of the workpiece. The furnace conditions are correlated to product quality via furnace process variables such as the air-to-gas ratio, furnace burner condition, furnace pressure, energy efficiency, adiabatic flame temperature (AFT) and furnace refractory condition. Operational practice recommendations are presented to minimize inhomogeneous heating, which results in inferior product quality, hot rolling model anomalies and toughness variations in the through-thickness direction.[6]

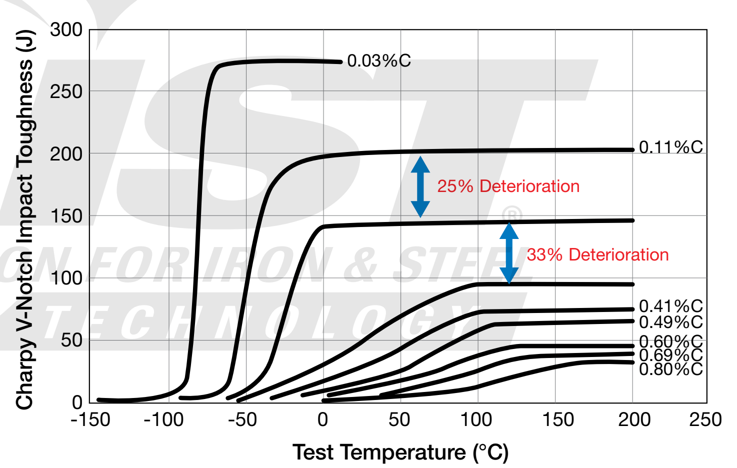
Variables such as billet size, push-out or dropout rate, air-to-gas ratios, excess O_2, furnace atmosphere affecting scale formation, and overall furnace efficiency all affect the heating behavior and ultimate kinetics of solubility of the microcarbides. The furnace heat loss profile can also affect the kinetics. Problems such as improper refractory construction, heat loss through openings, poor fitting inspection doors, inadequately maintained skids, and entry and discharge door problems all negatively affect the kinetics of the solubility process.[6] The effects of improper heating and billet soaking can lead to the following variations in final rebar mechanical properties supplied to the end user:

Figure 3



Charpy V toughness transverse direction S355 grade low carbon versus toughness.[5]

Figure 4



Impact toughness versus carbon content.

- Increased variability in yield strength within a given rolling schedule.
- Variable yield-to-tensile ratios in final hot-rolled product.
- Hard spots in MBQ and SBQ and rebar due to a variation in the volume fraction of martensite affecting cored properties and elongation.
- Overheating of the billets resulting in abnormal austenitic grain growth.

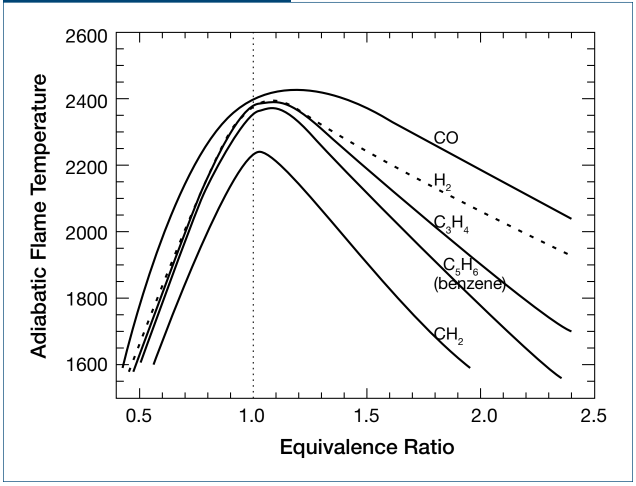
Importance of Reduced Soak Zone Temperatures — In the reheat furnace, the slab is heated via radiation off the refractory walls of the roof and sidewalls. The roof and sidewall refractory absorb heat from the flames emitted from the combustion burners. The adiabatic flame temperature (AFT) is affected by the fuel type, burner efficiency and air-to-gas equivalence ratio. The highest AFT translates into higher heat input, higher production throughput and maximum furnace efficiency. The optimum air-to-gas ratio also develops a furnace atmosphere that is conducive for good surface quality, high heat penetration into the slab, and optimal scale depth and viscosity. Fig. 5 illustrates the effect of different air-to-gas ratios (i.e., equivalence ratios) on the adiabatic flame temperature for different gases.

Since most furnaces consume natural gas, the maximum adiabatic flame temperature of 2,250 K occurs at approximately 1.10 equivalence ratio (10% excess air). Under these conditions, approximately half of the heat generated from the combustion of the fuel heats the steel. As the air-to-gas equivalence ratio increases, combustion efficiency declines and AFT decreases. There are several operational reasons that adversely increase the equivalence ratio.[8] Several furnace factors can create higher equivalence ratios resulting in improper heating of the steel and longer heating times:

- Cracked burner orifice plates, leading to sub-optimal flame temperature.
- Refractory cracks in furnace roof and/or side-wall, leading to air infiltration into the furnace.
- Low furnace pressure due to inefficient combustion fan mechanical performance (bearings, out-of-balance, component wear).
- Reduced working volume in the bottom zone of pre-heat and reheat section due to scale buildup.
- Improper dilute oxygen enrichment at combustion burner tip.
- Scale formation and viscosity.

Most commercial fuels are hydrocarbons. According to the stoichiometric ratio for full oxidation of a fuel, air/fuel mixtures fed to a combustor are classified as:

Figure 5



Air-to-gas equivalence ratio versus adiabatic flame temperature.[7]

- Lean mixtures (little fuel content, excess of air).
- Stoichiometric mixtures (with the precise or theoretical amount of fuel).
- Rich mixtures (more fuel than needed but excess fuel will pyrolyze to small-molecule fuels, and only small molecules appear at the exhaust).

Global Billet Reheat Furnace Operations — Numerous furnace operations throughout the world operate at both high reheat zone (>1,150°C) and soak zone furnace temperatures (>1,225°C), thereby overheating both plain carbon steels and microalloyed steels, leading to abnormal grain growth. Observations made at numerous mills around the world find high-temperature furnace operation even more prevalent on higher-carbon steels exceeding 0.20%C. The cause-and-effect relationship of these poor furnace heating practices have a detrimental effect on steel quality due to abnormal and variable grain size and inhomogeneous heating through the slab thickness. Coarser austenite grains translate into coarser ferrite grains in the final hot-rolled product. Also, overheating of steel results in thicker scale formation. The metallurgical consequences of thick scale formation go beyond simple surface quality issues and translate into mechanical property variability due to improper heating of the billets for both MBQ and SBQ before hot rolling. Observations made at numerous mills around the world find high-temperature furnace operation is often prevalent at mills producing high-strength, low-alloy (HSLA) microalloyed steels and higher-carbon steels exceeding 0.20%C. Niobium is effective in delaying austenite grain growth when high-temperature overheating conditions occur.

From a practical operational perspective, soak zone temperatures exceeding 1,250°C are deleterious to steel surface quality, toughness, yield, and mechanical property and cost performance. The decrease in yield is due to the formation of a heavy iron oxide scale. This scale can be several millimeters in thickness and converts to as much as 1 to 1.5% of yield loss. This loss in product translates into millions of dollars of scrap and reduced yield on an annual basis.

It is important to understand that kinetics is what ultimately controls the combustion reaction, effectiveness and efficiency. Thermodynamics indicates if the reaction is natural (i.e., may proceed in an isolated system) or artificial (i.e., requires some energy input from outside). Thermodynamics ensures that a fuel and air may naturally react, but if the kinetics is too slow, the combustion reaction is hindered. Two extreme cases of mixing are considered in combustion: combustion in a pre-mixed system, and combustion in the common-interface layer where non-premixed fuel and air come into contact. Also, the proper temperature and reheat time are critical to ensure that the various microalloy and/or alloy elements in high-strength thermomechanically controlled processed (TMCP) long product grades are properly put into solution in actual reheat furnace production conditions before rolling at the roughing and finishing mill.

Combustion Metallurgy Approach (CMA) — The definition of CMA is integration of the furnace process operational parameters and the combustion conditions and its effect on the billet quality as the billet exits the reheat furnace in terms of austenite grain size, homogeneity of temperature both through the billet and front-to-back and optimal scale formation. The reheat furnace process metallurgy directly affects the prior austenite grain size before the hot rolling deformation step. Although accepted universally as a vital processing step in the steel community, the influence of slab reheating and combustion metallurgy mechanisms are typically not connected to poor toughness results (i.e., low drop weight tear test (DWTT) and low Charpy values) or poor ductility and bendability. The random overheating of steel slabs, billets or blooms during the industrial reheat furnace operation causes abnormal grain growth. This randomness is sometimes predictable, but since proper dynamic reheat furnace control and practice adjustments are required in the moment to minimize these aberrations, no changes are made. Many mills often ignore the reheat furnace aberrations and no adjustments are made. In some cases, these aberrations are caused by burner, refractory and other combustion process control problems already presented. Consequently, mechanical properties through the thickness and across the width will vary considerably and deteriorate, especially toughness, bendability, ductility yield-to-tensile ratios and fatigue properties.

Structural ASTM Steel Specification Allowable Maximum Carbon Content

Numerous steel specifications applied to structural applications allow C maximum levels as high as 0.26%. Peritectic grades in the range of 0.11–0.16%C are quite often applied globally for structural long and plate products. There have been cases of some structural mill producers shifting back from low C to peritectic; however, this peritectic choice results in increased total activity-based cost (TABC) for steelmaking, casting and hot rolling operations. A lack of measuring and understanding the actual cost makes it difficult to calculate the benefits of this change to less than 0.10%C. Table 1 illustrates some ASTM specifications allowing for grades produced within this peritectic region.

The definition of lower-carbon steels in this paper is a carbon content less than 0.10%. For example, the current problem is that when customers place a steel order to a specification such as ASTM A529 or A572, unless a 0.10% maximum is specified by the customer, the mill can produce up to the maximum carbon level in lieu of the better material property performance achieved from lower-carbon steels. For even higher-yield-strength grades, ASTM A913 allows up to maximum 0.16%C for Grades 65 and 70. This change has also created some import situations and conflicts with poor end user performance.[9] If a producer opts that the peritectic approach is more cost-effective, that mill is not properly analyzing or understanding their total cost of production for these carbon-microalloyed steel grades. Since many end users rely on a given specification to meet their order requirements, although the specified chemical elements meet the composition range, the shipment is deemed acceptable. Herein, two potential problems might be experienced by the end user, specifically, material performance variability and major carbon level differences between heats and/or multiple suppliers and service centers. Recent communications with end users reveal that they do not realize the negative implications to their business when the peritectic grade is processed in their operation. Concurrently, the end users of these ASTM grades are demanding structural components with less mechanical property variability and consistence. For example, properties such as low-temperature toughness, formability, bendability, weldability, fracture toughness and fatigue performance are impaired when these higher-C grades are applied and applied from different steel mills and service centers, instead of the less-than-0.10%C lower-carbon steels, which would alleviate many of the quality problems at the jobsite.

Table 1

Selected ASTM Specification Carbon Maximum Levels[9]

ASTM specification	A242	A514[1]	A529	A572[2]	A588	A913[3]	A992
%C maximum	0.15	0.10–0.21	0.27	0.21–0.26	0.15–0.20	0.12–0.16	0.23

[1]Eight different grades with different maximum %C depending on grade
[2]Carbon maximum varies with cross-sectional area
[3]Carbon maximum increases with high-yield-strength grade

Low-Manganese MicroNiobium Long Products Approach

Recent steelmaking developments have successfully melted steel grades with as much as a 25% reduction in manganese content and a MicroNiobium replacement addition of 0.010 to 0.020%Nb for several structural and infrastructure plate, sections and long products. The result involves a steelmaking alloy raw material cost reduction, improved castability, reduced internal manganese sulfide centerline segregation and less microstructural banding in the hot-rolled slabs, yielding a more homogeneous pearlitic microstructure. The applications within the infrastructure segment are growing due to the competitive nature of this product segment and especially attractive to the MBQ sector. Much has been published regarding the effect of Mn on centerline segregation. Delamination and cracking related to segregations are mostly observed at the centerline of hot-rolled products. The delamination is related to a heavy concentration of manganese sulfide inclusions originating from centerline segregation in slabs, resulting in numerous customer complaints. Similar delamination or cracking is also observed at locations away from the mid-thickness plane of hot-rolled products during forming operations at customers. Even in relatively homogeneous microstructures, segregation may often lead to the rejection of materials and increased external cost of quality for the steel operation. Metallographic investigation reveals a segregation line with an abundance of manganese sulfide stringers at the off-center location like observations in cases of centerline defects. Centerline segregation is a well-understood phenomenon but the presence of off-center segregation line in hot-rolled products has not been systematically studied before.[10] Intercolumnar cracks in slabs can be filled with segregated elements in addition to Mn. Through the course of this MicroNiobium-low-manganese approach development, the market experienced increasing FeMn prices creating the global supply-demand imbalance. However, as this paper reports, a further analysis of the benefits is well beyond just a simple alloy cost reduction at the meltshop via an FeNb reduction and MicroNiobium addition. During the hot rolling of these low-carbon-manganese-MicroNiobium steels, delay of the pearlite transformation leads to a finer interlamellar spacing and finer grain size due to a shorter transformation time and thereby contributing to a strength increase even at lower Mn and C concentrations. Some of the other beneficial effects besides reducing alloy cost from the lowering of the Mn content by as much as 0.40%Mn are:

- Lower amount of cold additions to liquid steel (possible saving of energy).
- Lower P contamination from FeMn alloy.
- Lower Mn centerline segregation in the slab/plate.
- Reduced banding in hot roll microstructure.
- Lower carbon equivalent (better weldability).
- Improved robustness and less yield strength and tensile strength scatter.
- Finer and more homogeneous grain size through thickness and across width.
- Improved toughness and lower DBTT (ductile-to-brittle transition temperature).

Research and development on low Mn-low Nb construction steels has recently been commercialized.[11] The approach involves the application of simple conventional rolling schedules and reheat and hot rolling practices. Implementation is seamless and feasible in industrial operations. In the past, there was limited research into such products for two primary reasons. First, when secondary and tertiary processes such as hot forging, drawing and cold forging were applied to medium- and high-carbon steels, some think that the effects of controlled rolling may be lost through the process. Secondly, Nb has a lower solubility in austenite in comparison with low-carbon steels at the same temperature. However, these trials have exhibited excellent toughness results even in medium-carbon peritectic S355 structural steels for construction applications at very economical cost, as shown in Table 2.

The intent of this work is to study existing carbon (peritectic) compositions and replace the vanadium with niobium and make a significant reduction in the manganese level for these 345 MPa grades. The next step is to consider a similar reduction in Mn strategy even for lower-strength steels such as 235 MPa and 275 MPa as a cost reduction opportunity. The knowledge gained from this work illustrates the possibility

Table 2

Medium-C-Low-Mn MicroNiobium Mechanical Properties[*11]*

Sample	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Impact strength @ –20ºC	Impact strength @ 0ºC	Impact strength @ +20ºC
Aim	345	470	21.0	—	≥34	—
II-16 mm	405	525	28.5	150	170	160
III-16 mm	410	535	33.0	150	170	160
IV-40 mm	455	615	22.0	160	155	180

* Mn level reduced from Standard 1.45 to 1.15%Mn and 0.010%Nb at 0.16%C (peritectic and Mn/S is reduced from 181 to 144)

of making Mn reductions and significant cost savings. There have been situations where the aim is to produce S275 and the mill actually produced S420 MPa structural grades with improved toughness and less microstructural banding. The solid solution strengthening equation is shown in Eqs. 2 and 3 per Gladman and Pickering:[12]

$$\text{Yield strength (MPa)} = 53.9 + 32.3\%\text{Mn} + 83.2\%\text{Si} + 354\%\text{Nf} + 17.4\text{d-1/2} \quad \text{(Eq. 2)}$$

$$\text{Tensile strength (MPa)} = 294 + 27.7\%\text{Mn} + 83.2\%\text{Si} + 3.85\%\text{Pearlite} + 7.7\text{d-1/2} \quad \text{(Eq. 3)}$$

Table 3 illustrates the solid solution strengthening effect at various Mn concentrations.

Table 3

Manganese Solid Solution Strengthening

%Mn	Contribution to yield strength (MPa)	Contribution to tensile strength (MPa)
0.30	10	8
0.60	16	14
1.00	32	28

Special Bar Quality Developments

The technological development of value-added applications for niobium (Nb)-microalloyed long products and forging steels continues to increase globally, meeting more demanding end user requirements. The global end user community is specifically seeking improved energy absorption behavior, improved fatigue life, better crack arrest capability, reduced component mass, and more efficient production with reduced emissions throughout the product life cycle. Within the forging sector, additions of microalloying elements affect the rate of grain growth during the heating of blanks, recrystallization parameters of deformed austenite, temperature of gamma-alpha transformation at cooling, as well as the contribution to precipitation hardening of the ferrite constituent. Development of a seismic-resistant rebar, fine grain forgings and construction sections and plates exhibiting better yield-to-tensile ratio consistency, improved energy absorption at low temperature and better weldability is described. Another rapidly expanding global niobium metallurgical sector involves both medium- and high-carbon long products. Microadditions of 0.005 to 0.020%Nb exhibit improved formability during manufacturing, uniform grain size, as well as enhanced mechanical property performance compared with traditional non-Nb-bearing treated medium- and high-carbon steels.

Mechanical properties improvements with the addition of Nb in rebar and structural shapes have been cross-applied to automotive structural components, such as coil springs. For example, a North American vehicle front suspension coil spring composed of 0.51%C with Mo-V-Nb was developed and commercialized with improved mechanical properties compared to conventional springs. A similar effect was observed as in rebar and other long product applications when adopting 0.035%Nb in a 9259 engineering alloy spring steel grade. The improved properties are attributed to the grain refinement, more homogeneous microstructure, microalloy carbonitride precipitate morphology and precipitate strengthening provided by Nb. The chemistry of the Nb-modified spring steel is shown in Table 4.[13]

The improvement in hardness at temper temperature has translated into increased strength, better fatigue endurance limits and good fracture toughness, thereby allowing for a lighter-weight design coil spring. The fatigue and fracture toughness comparison of standard SAE9259 is compared to the Nb-modified SAE9259 in Figs. 6 and 7, respectively.[13]

This Nb-V-Mo modified coil spring steel has resulted in the reduction in weight of a coil spring by approximately 15%, improved fatigue resistance by

Table 4

Coil Spring Chemistries, %

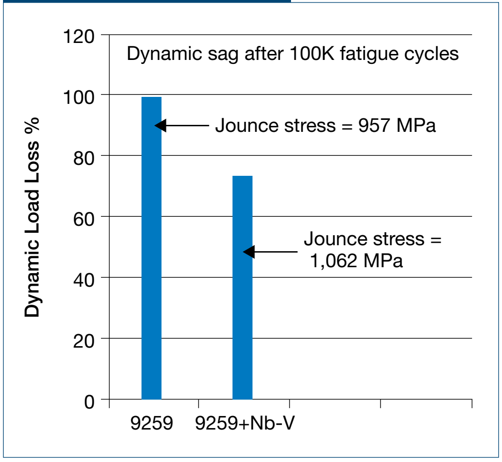
	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Nb	N (ppm)
SAE9259	0.61	0.86	0.014	0.021	0.78	0.008	0.008	0.51	0.008	0.005	0.002	55
V-SAE9259	0.60	0.81	0.020	0.017	0.85	0.007	0.009	0.51	0.003	0.100	0.002	110
Nb-V-MoSAE9259	0.51	0.69	0.016	0.020	1.31	0.007	0.012	0.45	0.040	0.100	0.035	130

12% and improved fracture toughness by 27% compared to the conventional 5160 or 9259 and/or the V-modified 9259. The resultant Nb-V modified grade exhibits improved yield and tensile strength, which translates into better cyclic fatigue life and improved fracture toughness. The adjusted steel chemistry, grain refinement, Nb-V(CN) precipitation strengthening and overall lower volume fraction of hard oxide inclusions results in improved properties. This application illustrates the complimentary synergy between Nb and V in these higher-carbon engineering tool steels. The grain refinement effect leads to the improved dynamic load loss performance and the improved fracture toughness and ductile fracture. In actual operation, the Nb-to-V stoichiometric ratio has been reduced, thereby lowering the cost of the V and MicroNiobium additions at 0.020% Nb.

Another SBQ application involves Nb in high-carbon eutectoid steels. The growth in this market continues. An advance in improving a 1080 grade steel by the addition of a microalloy was not warmly welcomed because of an incomplete understanding of its effectiveness. Tests at two plants later showed this method to be beneficial for products such as pre-stressed concrete wire rod, tire cord and medium-carbon spring steels. The MicroNiobium alloy approach is applied in higher-carbon steels and medium-carbon bar products exceeding 0.20% carbon to improve the mechanical property robustness of the steel via grain refinement. This mechanism allows grain refinement from billet to bar to wire rod to be more homogeneous, resulting in improved surface quality, increased productivity and reduced scrap rates throughout the process supply chain, thereby reducing the overall operational cost per ton. A study was made to optimize the Nb composition in a 1080 steel to determine the best drawing ratio, reduction ratio, ductility and surface quality, and final mechanical property performance at the end user wire processor. The results indicate that the MicroNiobium addition of only 0.02% Nb provides an improved product robustness, reducing the cost of quality and improving productivity by as much as 10%. The results from this 1080 eutectoid wire rod study provides the fundamental metallurgical understanding that explains the improved properties. Based on these results, the same MicroNiobium methodology is applied for other carbon steels. Such a comprehensive study is not necessary as it is possible to cross-apply the optimized low MicroNiobium composition (0.005–0.020% Nb) for 1080 to the lower-carbon steels (i.e., the 0.70%, 0.50% C and 0.35% C). Thus, in these steels the two-fold benefit of MicroNiobium is: (1) prevention of abnormal austenite grain growth during reheat furnace aberrations (CMA) and (2) minimization of the interlamellar pearlite spacing improving mechanical properties.[14]

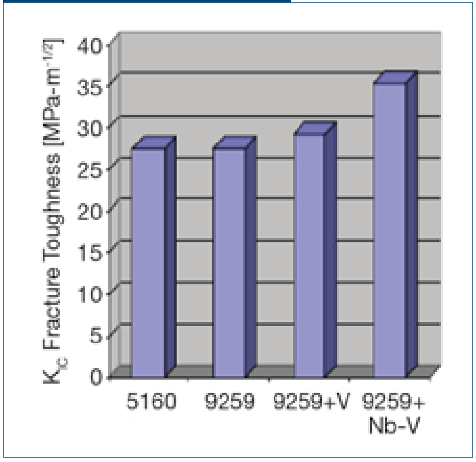
The application of niobium in high-carbon steels enhances both the metallurgical properties and processability of long products. Such process and product metallurgical improvements relate to the Nb-pinning effect of the austenite grain boundaries

Figure 6



Dynamic sag loss comparison.

Figure 7



Fracture toughness comparison.

in microalloyed 0.25 to 0.95%C steels, minimizing abnormal grain growth during the reheat furnace process prior to rolling. Consequently, Nb microalloyed medium- and high-carbon, long product steel applications have been developed. The MicroNiobium alloy approach is described and correlated to a variety of medium- and high-carbon steel grades and applications. Development opportunities and applications span automotive coil springs, eutectoid rail steels, alloy tool and die steels, automotive fasteners, reinforcing bars, wire, and tire rod. The detailed analysis of the optimization at 0.018% Nb in 1080 eutectoid pre-stressed concrete wire rod provided the basis for this metallurgical strategy. This approach contributes to the achievement of desired ultrafine-grain, homogeneous high-carbon steel microstructures that exhibit superior toughness, strength, fatigue performance, less mechanical property variation in the final hot-rolled product, reduced cost of quality and improved weldability. Cross-application of 0.005 to 0.020% Nb provides for more robust long products via austenite grain boundary pinning during reheating and very fine interlamellar pearlite spacing during hot rolling. The improvement in the cost of quality far exceeded the additional alloy cost for the MicroNiobium addition.[15]

Conclusions

The process and physical metallurgy synergy is vital in conjunction with the materials science engineering connection in understanding and properly executing the successful transfer of new and advanced long products from the laboratory to industrialization. The integration of steelmaking, continuous casting, and hot and cold rolling is critical to properly understand the root-cause process metallurgical parameters affecting the physical metallurgy of the desired products. Opportunities exist to incorporate some SBQ-type metallurgical practices to MBQ production practices in the interest of reducing operational cost and improving productivity and quality in commodity MBQ production. The future trends in some long product steelmaking shops involve both a reduction in sulfur and phosphorus levels (nearly a 50% reduction) as well as more restrictions on residuals. These reductions in sulfur and phosphorus result in reduced diverts and scrap, as well as increased rolling speeds and tons-per-hour production rates at the rolling mill. Certainly, these residual reductions enhance the quality and bar performance at the customer level. The reduction of carbon to less than 0.10% with MicroNiobium improves castability, steel robustness and weldability. The complementary development of new generation value-added low-carbon-low-manganese MicroNiobium structural steels for both low and high yield strength offer improved toughness, bendability and ductility at reduced operational cost. Another major development trend involves the effects of the reheating process operational variability (CMA), which significantly affect austenite grain size, recrystallization behavior, and final microstructure and ductility in both MBQ and SBQ products.

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