COST EFFECTIVE ALLOY OPTIMIZATION DESIGN STRATEGY FOR STRENGTH AND DUCTILITY PROPERTIES OF STRUCTURAL STEELS *

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Abstract

Major costs in the production of both flat and long commodity grade structural steel products include alloy, labor and energy. Flat and long commodity grade structural steels such as ASTM A36, ASTM A527Gr50, S235, S275, S355 and other equivalent world societal standards represent over 500 million annual tons worldwide. These simple commodity grades consist of a minimum of three base common alloying elements, carbon, manganese, silicon and then can be supplemented with microalloying elements of either vanadium or niobium. Since 2016 raw material costs for two of the five alloying elements in these commodity grade structural steels, FeMn and FeV, have risen significantly and/or have become volatile making it difficult to maintain stability in profitability for these commodity grades. For steel plants producing hundreds of thousands and in some cases over a million tons annually of these common structural steel grades because of the significant alloy cost increase for Mn and V alloy additions has squeezed profitability of these grades. These grades typically represent the base loading for cost controls in most all steel plants and hence a significant cost increase or volatility in two of the five elements used for these grades having a negative effect on overall production costs. However, with a proper strategy for alloy designs working in conjunction with the mills existing processing capabilities to achieve the desired end metallurgy/mechanical properties, alloy costs and operational efficiencies can be realized.

Keywords: Optimization; Strategy; Niobium; Microstructural Modeling

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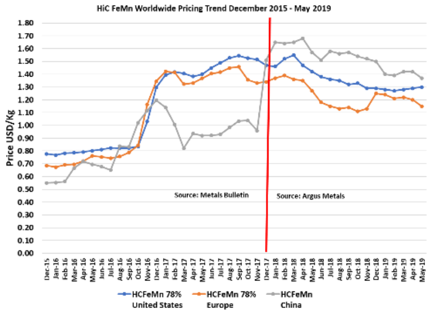
1 INTRODUCTION

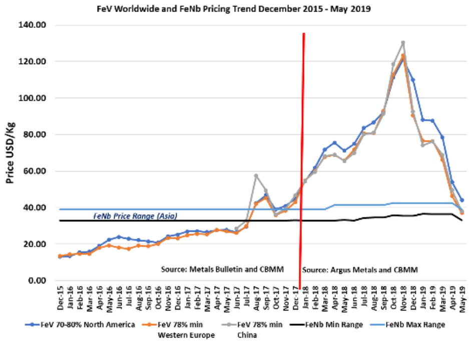
Utilizing a proper understanding of the contribution to metallurgy and the final mechanical properties of the three basic elements of C, Mn and Si and supplemental elements of Nb and V can result in significant cost savings in the production of simple structural steel commodity grades. Alloy optimization can result in cost savings of US $2/ton to US $20/ton or in some cases higher. In a mill producing typically from 200,000 tons up to 1 million tons annually can represent cost saving in alloy of US $400,000 up to US $20 million annually [1]. Because of the significant opportunity for cost savings going to the financial bottom line, potential opportunities for alloy optimization is something that cannot be ignored and must be explored. Many worldwide commodity flat and long products structural steel producers have already taken steps in alloy optimization of their production and have realized significant cost savings. An understanding of what creates strength and ductility for any given structural steel microstructure is what is needed to achieve these cost savings. Strength and ductility for any structural steel are obtained from three metallurgical mechanisms or “building blocks”: a) grain size refinement, b) solid solution and c) precipitation. If better engineering of these contributions from the three metallurgical “building blocks” can be realized for a given mills processing capabilities, alloy costs can be minimized resulting in significant annual cost savings. The correct use of these factors brings in addition process/mechanical property stability resulting in corresponding reductions in yield losses and additional operational cost savings. The use of practical metallurgical modeling tools along with mill data to determine process control capabilities can also assist in alloy/process designs or strategy for further cost optimization.

2 ALLOY OPTIMIZATION STRATEGY

With the recent increase and volatility of Mn and V in the past 3 years, Figure 1 [2], it is imperative these days that an optimized cost-effective approach strategy to alloy design for strength and ductility be implemented.



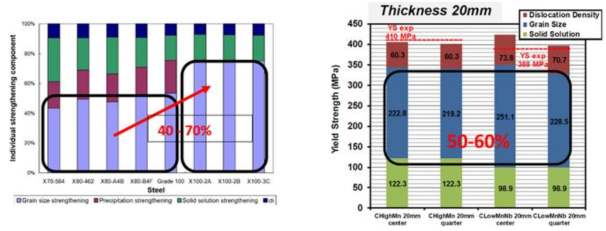
HiC FeMn published world pricing



FeV and FeNb published world pricing

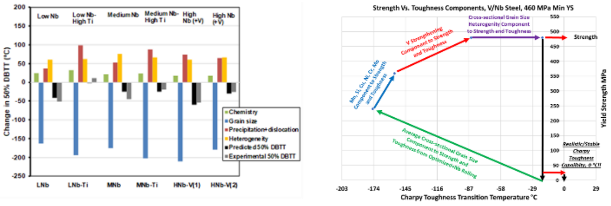
Figure 1: HiC FeMn, Fe and FeNb published pricing for the past 4 years. Note that HiC FeMn has stabilized at a higher price for the past 2 years and FeV has been very volatile and still much higher than 4 years ago.

Mechanical properties of any structural steel for a given microstructure are predominately driven by the average grain size (strength) and cross-sectional homogeneity/heterogeneity/distribution of the grain size (ductility – toughness, elongation, formability, fatigue, flatness/shape) [3]. Strengthening component of average grain size contributes to 40-70% of the strength, while average grain size/ homogeneity /heterogeneity/distribution through the cross-section represents two very significant contributing factors to ductility properties. Contributing components to strength and ductility can be seen in Figure 2 [4, 5, 6].



Strengthening components of API steel, blue grain size, red post rolling precipitation, green solute strengthening, dark blue strain/dislocation density

Strengthening components of S355 steel, blue grain size, red strain/dislocation density, green solute strengthening, no post rolling precipitation strengthening available



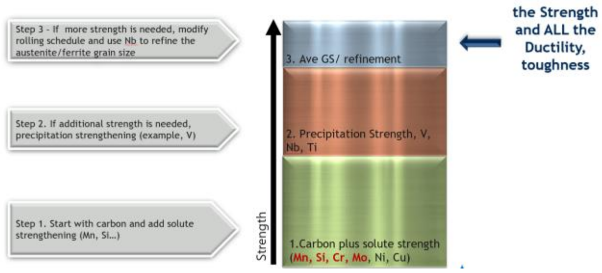
Ductility/toughness components of various structural steels, blue average ferrite grain size, yellow heterogeneity, red post rolling precipitation, green chemistry/microstructure

Strength and ductility/toughness components illustration from diagram on left of one of the steels shown.

Figure 2: Strength and ductility components illustrated

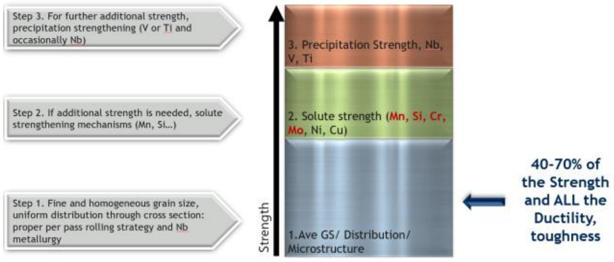
In many of the commodity grade structural steels strength is the main requirement with minimal ductility/toughness requirements. This means that using an updated alloy design strategy that is geared to alloy optimization for strength and ductility/toughness versus the older outdated alloy design strategy is the best method to realize minimum alloy costs but with satisfactory/stable strength and ductility/toughness properties. Figure 3 shows the difference between the older outdated strategy vs. a newer cost-effective strategy.

✦Conventional, non-optimized approach to designing strength without regard to ductility



Outdated, conventional approach to alloy design

✦Optimized approach to designing strength including ductility



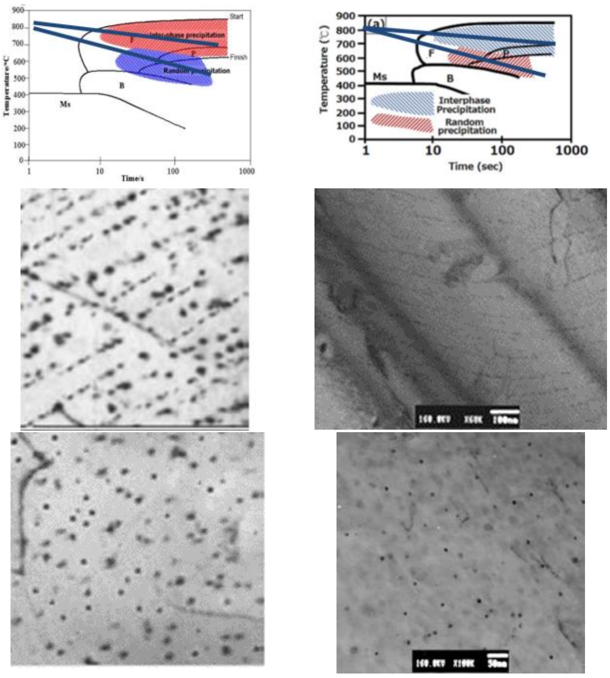
New, optimized cost-effective approach to alloy design

Figure 3: Illustration of outdated conventional vs. new optimized cost-effective approach to alloy design for strength and ductility

As illustrated in Figure 3, since 40-70% of the strength and ALL the ductility properties come from the average grain size/distribution for a given microstructure, it only makes common sense to start the alloy design strategy for the process around this point. This does not mean that severe TMCP type rolling or substantial additions of Nb are needed, it only means that for a given grade requirements and processing capabilities that the thought process should be centered around how to achieve a reasonable level of grain refinement and homogeneity through the cross section. Once Step 1 is completed, then as shown in Figure 1 solid solution strengthening additions and post rolling precipitation strengthening mechanisms, Step 2 and Step 3, typically Mn for solid solution strengthening and V for post rolling precipitation in commodity grade structure steel, should be done with a recognition of the current cost of these two alloys. In addition, it is not widely understood or considered the "efficiency factor" of post rolling precipitation strengthening mechanisms. Post rolling precipitation strengthening mechanisms requires a significant volume of fine precipitates to generate the strength as described in the Ashby-Orowan equation (Equation 1) [7] where "*f*" equals volume fraction of precipitate and "*x*" equals the average diameter of the precipitates.

$$\boxed{\Delta\sigma_{ppt} = \frac{5.9\sqrt{f}}{\bar{x}}\ln\left(\frac{\bar{x}}{2.5\times10^{-4}}\right)} \quad (1)$$

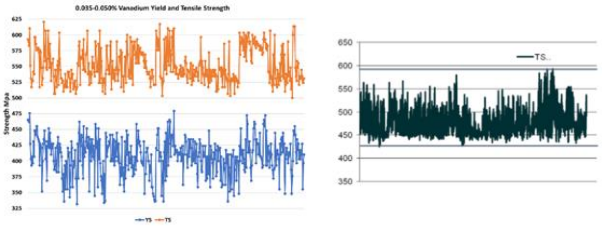
Strength from this mechanism comes from either interphase precipitation, which results in the most effective strengthening mechanism, during post rolling cooling or random precipitation, less effective but most commonly used in the production environment, which occurs upon final plate/coil/bar cooling. The metallurgy requires, regardless of the microalloying element (V, Nb, Ti) to have a significant volume of microalloy still in solution upon entry to the post rolling cooling phase that could potentially precipitate. How much microalloy is still in solution being dependent on prior processing parameters in some cases such as Ti going all the way back to the LMF process in steelmaking is typically an unknown. Then the post rolling cooling rate must be controlled precisely for interphase precipitation to occur or the post rolling final cooling must be in the correct temperature range for random precipitation to be effective, Figure 4 [8, 9]. Very few steel producers control the post rolling cooling in a way that would promote effective/optimum use of either interphase or random precipitation and hence results in variable stability of final mechanical properties, Figure 5, "wasting" costly alloy additions. Most steel producers just add some significant volume of the microalloy, typically from 0.030-0.100%, hoping that some amount of precipitation strengthening will occur within their natural post rolling cooling process. This is not an efficient or cost-effective approach to commodity structural steel production these days.



VN post rolling precipitation example

TiC post rolling precipitation example

Figure 4: Example of time/temperature where interphase/random precipitation of V and Ti occurs and resultant precipitate morphology. IN almost all structural steel applications random precipitation is the main form of this strengthening mechanism, but not very efficiently controlled in production.



YS/TS of V precipitation of hot rolled commodity structural steel plate

TS of Ti precipitation hot rolled commodity structural steel coil

Figure 5: Examples of YS and TS of V and Ti post rolling production precipitation strengthening stability due to lack of post rolling cooling process control.

3 COST-EFFECTIVE APPROACH

It has been well established that during hot rolling, controlling the austenite grain size and recrystallization behavior can contribute to a minor, but effective effect in developing that first metallurgical building block, i.e. Step 1[10]. By utilizing dilute amounts of Nb microalloying during hot rolling austenite grain size can be positively modified. This modification can allow for a reduction in solid solution strengthening or post rolling precipitation strengthening mechanisms, primarily Mn and V, resulting in alloy cost savings and stable mechanical properties. Regarding Mn solid solution strengthening contribution to strength utilizing equations for YS and TS developed by Pickering (2) [11], the contribution of Mn to both YS and TS can be calculated, Table 1.

$$YS = 53.9 + 32.3\,Mn + 83.2\,Si + 354.2\,\sqrt{N_{sol}} + \frac{17.4}{\sqrt{d}}$$

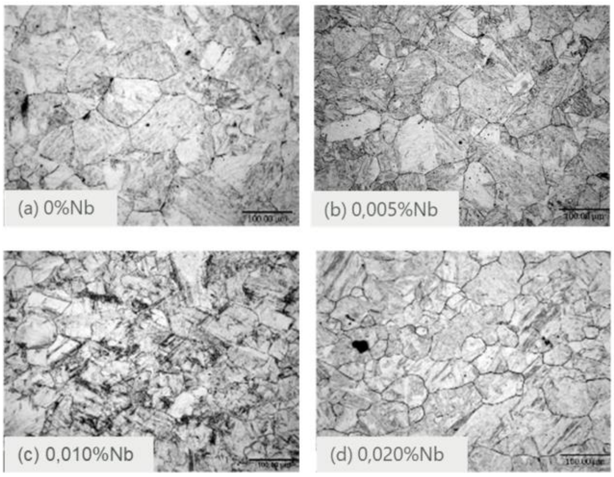
$$TS = 294.1 + 27.7\,Mn + 83.2\,Si + 2.85\,Pearl + \frac{7.7}{\sqrt{d}} \qquad (2)$$

Table 1: Contribution of Mn to YS and TS

% Mn	Contribution to YS	Contribution to TS
0.30	10 MPa	8 MPa
0.50	16 MPa	14 MPa
1.00	32 MPa	28 MPa

It can be seen from Table 1 that 0.30 or 0.50 Mn only contribute 10-16 MPa of YS and 8-14 MPa of TS. So, if Mn costs can be optimized by reducing Mn by 0.30 or 0.50%, then replacement of YS and TS needs to come from another strengthening component. Within the Pickering strength equation is also grain size "d". If the average final ferrite grain size can be changed by only 2 µm, 16 MPa of YS and 8 MPa of TS can be realized as calculated in the Pickering equation. This means that up to 0.50% Mn could be reduced successfully with a minor change in the final ferrite grain size, hence improving alloy costs.

Recent research by Zhe [12] has shown that dilute amounts of Nb, even at rolling temperatures >950 °C can refine the austenite grain size, Figure 6.



Dr Zhe Cui – PhD Thesis University of Sheffield (2016)

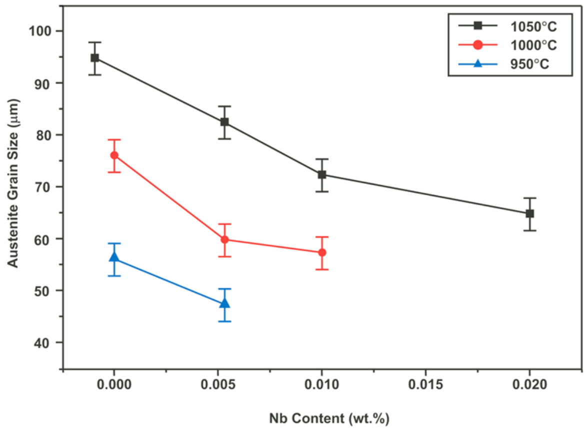
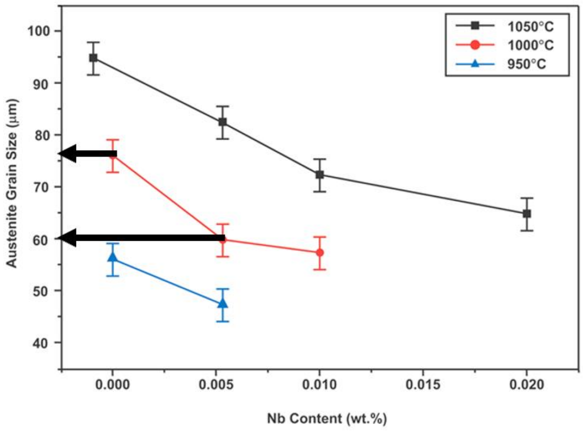


Figure 6: Austenite grain size evolution of 0.08% C steel after 20 second holding period at 1000 °C followed by water quenching vs. Nb level

Utilizing this information, this shows at 1000 °C a dilute Nb addition of 0.010% can reduce the austenite grain size from 80 µm to 60 µm resulting in a 2 µm (16 µm to 14 µm) final ferrite grain size reduction, Figure 7 [13].



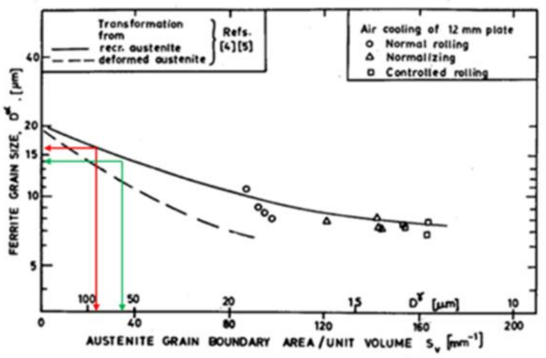


Figure 7: At 1000 °C a dilute Nb addition of 0.010% can reduce the austenite grain size from 80 µm to 60 µm resulting in a 2 µm (16 µm to 14 µm) final ferrite grain size reduction

Using current published HiC FeMn pricing for Europe and average FeNb pricing at the end of May 2019, a reduction of 0.30-0.50% Mn with a dilute addition of 0.010% Nb can result in a cost savings of USD $1.31 - $4.59/ton. Most structural mills will produce between 250,000-500,000 annual tons of lower strength S235, S275 and S355 or equivalent grades which means if Mn can be reduced in these grades with a dilute Nb addition of 0.010%, annual cost saving ranging from USD $327,500/$655,000 - $1.15-$2.30 million annually could be realized. This does not include any significant cost savings that can be realized from productivity enhancements, inventory minimization or improved yield performance from an optimized alloy design.

A similar approach can be used to realize a reduction or complete removal of V with minor amounts of Nb or even a combination of V/Nb with reduced Mn, Figure 8.

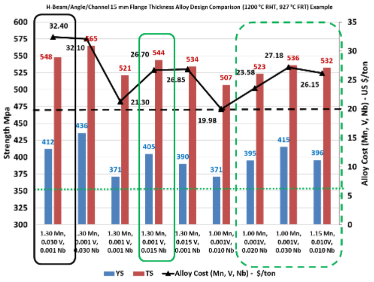
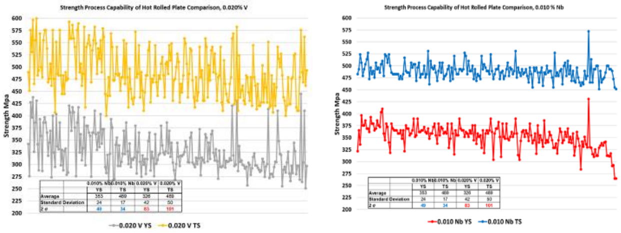


Figure 8: Example of alloy optimization modeled simulated strength possibilities for 15 H-beam considering Mn, V and Nb

Alloy optimization can be accomplished by using actual production chemistry, basic processing (reheat/FRT) and resulting mechanical properties to calibrate empirically designed physical prediction models to simulate possible options as was illustrated in Figure 8. The goal is not to change anything in the existing process parameters of the production, but to design and optimized alloy to fit the existing production process parameters. This type of modeled simulation using actual mill data can allow for a more robust approach to a possible cost- effective optimized alloy design that can be used for trial. Once the trial is completed, fine tuning of the alloy can be done as required and if desired minor optimization of the processing can be implemented using available tools such as MicroSim® austenite evolution modeling.

4 RESULTS AND EXAMPLES

In optimization of Mn and V with dilute amounts of Nb, as was seen, the austenite grain size is affected during hot rolling. Affecting austenite grain size and hence final ferrite grain size is much easier to implement consistently as a strengthening mechanism than that of post rolling precipitation strengthening, Figure 9.



0.020% V hot rolled structural steel plate production YS and TS

0.010% Nb hot rolled structural steel plate production YS and TS

Figure 9: ASTM A572 Gr50 post rolling precipitation strengthening vs. austenite/ferrite grain size refinement strengthening comparison of V and Nb in hot rolled structural steel plate production

Minor changes in final ferrite grain size as describe prior as being as little as a 2 µm is enough to allow for a 0.50% Mn reduction and still produce the same strength level. This concept was successfully implemented at Nanjing Iron and Steel (NISCO) in 2017 in structural steel 345 MPa minimum YS up to 40 mm in thickness. Strength, toughness, flatness, UT performance, etc. have been easily achieved in mass production. In addition, one single slab chemistry design has been successfully used to feed three different plate mills, standardized rolling strategies among the three plate mills and produce several different plate grades/versions of 345/355 minimum yield strength products. Example results can be seen in Figure 10.

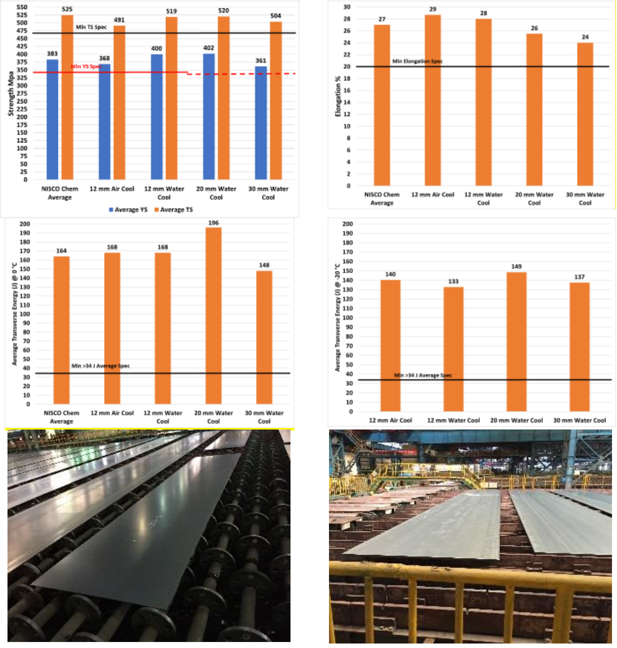


Figure 10: Example of 0.50% Mn reduction with a dilute 0.010% Nb addition mechanical properties and flatness at NISCO

Metallographic comparisons of the higher Mn no Nb alloy design vs. the lower Mn dilute 0.010% Nb alloy design shows an approximate difference of an average 2 µm ferrite grain size finer with the 0.010% Nb steel, Figure 11. This results in an increase in strength coming from the ferrite average grain size component to compensate for the strength reduction from the solute strengthening component from the lower Mn content.

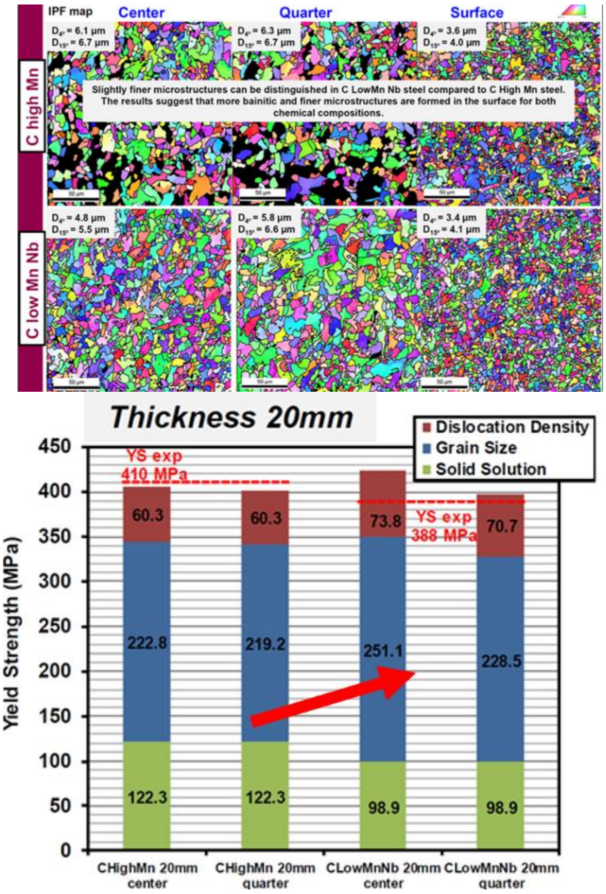


Figure 11: 20 mm microstructure and grain size comparison of higher Mn no Nb and lower Mn with 0.010% Nb structural steel along with analysis of various strengthening components analyzed in the microstructure evaluation. Note the average ferrite grain size difference at the ¼ and center thicknesses close to a 2 µm difference.

Obvious improvement in slab centerline alloy segregation/macroetch quality and corresponding microstructural banding improvement can be seen in Figure 12.

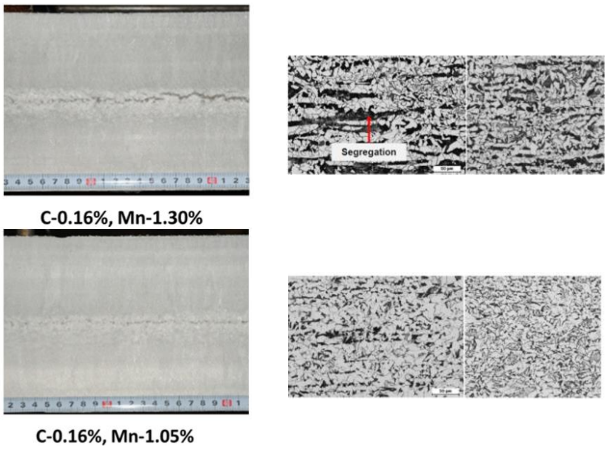


Figure 12: Slab macroetch and microstructural banding comparison between higher and lower Mn

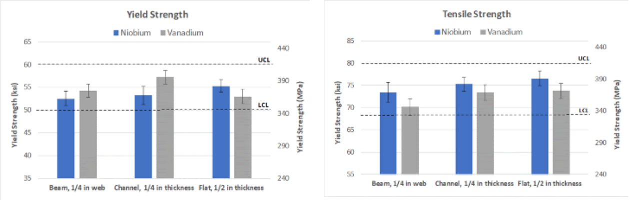
MicroSim® PM modeling of the austenite grain size evolution of the C/Higher Mn alloy design vs. the C/Lower Mn 0.010% Nb design also show the same trends in the austenite evolution. As seen in the final microstructures with finer overall ferrite grain size and as shown in the MicroSim® austenite evolution modeling at the end of the rolling process is an overall finer austenite evolution and a better cross-sectional distribution, Table 2.

Table 2: MicroSim® austenite evolution modeling output comparison of austenite grains between C/Mn vs. C/Mn/Nb 20 mm plate steel

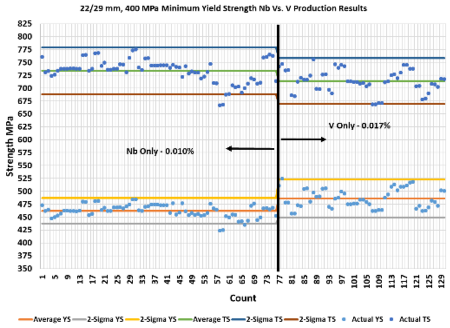
	Average Austenite GS µm	**90% Max Austenite GS µm (Dc 0.10)**	**Maximum Austenite GS µm**
0.16%C/ 1.40% Mn	23	73	254
0.16%C/ 0.90% Mn/ 0.010% Nb	18	50	192

Since the increase in FeMn costs starting in late 2016 and then FeV pricing increase/volatility starting in late 2017 there has been a strong interest by many structural steel producers to optimize their alloy costs for Mn and V additions. This has been done in plates, hot strip, H-beams, angles and rebar around the world. In some cases, there is already a purposeful Nb addition, such as 0.010% that can be increased by 0.010% Nb to 0.020% Nb and then the Mn reduced by 0.30% or more allowing for USD $1-2/ton of cost savings depending on Mn and Nb pricing. Additional examples of grades and products that have been optimized for Mn and V utilizing Nb are as follows, Figure 13 [14]:

Hot Strip – S355 up to 16 mm, Mn reduction with 0.010% Nb, Mn reduction V removed with 0.025% Nb
Plate – S355, AH32/AH36, AH/DH36, SM490
H-beams/Angles – S355, A572 Gr50
Rebar – 400 MPa min YS



H-beams and angles Nb alloy optimization of V



400 MPa minimum YS rebar Nb only and V only comparison. Note the overall improved 2-sigma control with Nb.

Figure 13: H-beams, angles and rebar examples of Nb alloy optimization of V. Note the improvement in 2-sigma control with Nb which is typical of all products seen to date when using Nb in alloy optimization.

5 CONCLUSION

Two of the five main elements used in the production of commodity grade structural steels have increased and/or have become volatile over the past 2 years applying profit pressure on many steel producers around the world who rely on these commodity grades to cover their base production costs. It has been demonstrated that with a proper understanding of the three main building blocks for metallurgy/mechanical properties and how to use each element properly via alloy optimization production costs can be improved. This fundamental understanding can be applied to any structural steel shape rolled. Improvement in standard deviation of mechanical properties when using the proper building blocks is typically seen further improving yields and costs. Tools such as calibrated empirical physical prediction models and MicroSim® austenite evolution modeling can be used to properly optimize the alloy design and process parameters for overall optimization of production costs of structural steels.

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