

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

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## Abstract

Alloy, labor, and energy made up for major costs in the production of flat and long commodity-grade structural steel products. 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. Carbon, manganese, and silicon constitute the minimum base of alloying elements for the commodity structural steels. This base can be then 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. This is making difficult to maintain stability in profitability. 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 have squeezed profitability. Commodity-grades usually represent the base loading for cost controls in most steel plants. Hence a significant cost increase or volatility in two of the five elements used for these grades will have a negative effect on overall production costs. However, with a proper strategy for alloy design 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.

## 1 INTRODUCTION

Significant cost savings in the production of simple structural steel commodity grades can be realized if 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. 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 an alloy of US \$400,000 up to US \$20 million annually [1]. Alloy optimization is something that cannot be ignored and must be explored because of the significant opportunity for cost savings. 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 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 can be realized for a given mill 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 [2], it is imperative these days that an optimized cost-effective approach strategy to alloy design for strength and ductility be implemented.

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It is important these days that an optimum cost-effective alloy design is implemented. International prices of FeMn increased to, approximately 1.4 US\$/ton, from Dec, 16 to Oct, 19, from 0.7 US\$/ton since Dec, 15. FeV, around less than 20 US\$/ton on Dec, 15 raised to 40 US\$/ton on Dec, 17, then kept increasing up to 120 US\$/ton by Nov, 18 and then went back to 40 US\$/ton by Oct, 19; a very volatile behavior.

Mechanical properties of any structural steel, ie, strength, ductility, toughness, elongation, formability, fatigue, flatness/shape are predominately driven by the average grain size (strength) and cross-sectional homogeneity of the grain size (ductility – toughness, elongation) [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 1 [4-6].

In many of the commodity-grade structural steels, strength is the main requirement with minimal ductility/toughness requirements. To achieve this, an updated alloy design strategy that is geared to alloy optimization for strength and ductility/toughness is necessary. Figure 2 shows the

difference between the older outdated strategy vs. a newer cost- effective strategy.

As illustrated in Figure 2, 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. Once this “Step 1” is completed, 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.

Post rolling precipitation strengthening mechanisms require 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 bar” equals the average diameter of the precipitates.

$$\Delta\sigma_{ppt} = \frac{5.9\sqrt{f}}{\bar{x}} \ln\left(\frac{\bar{x}}{2.5 \times 10^{-4}}\right) \quad (1)$$

Metallurgy requires, regardless of the microalloying element (V, Nb, Ti) to have a significant volume of microalloy

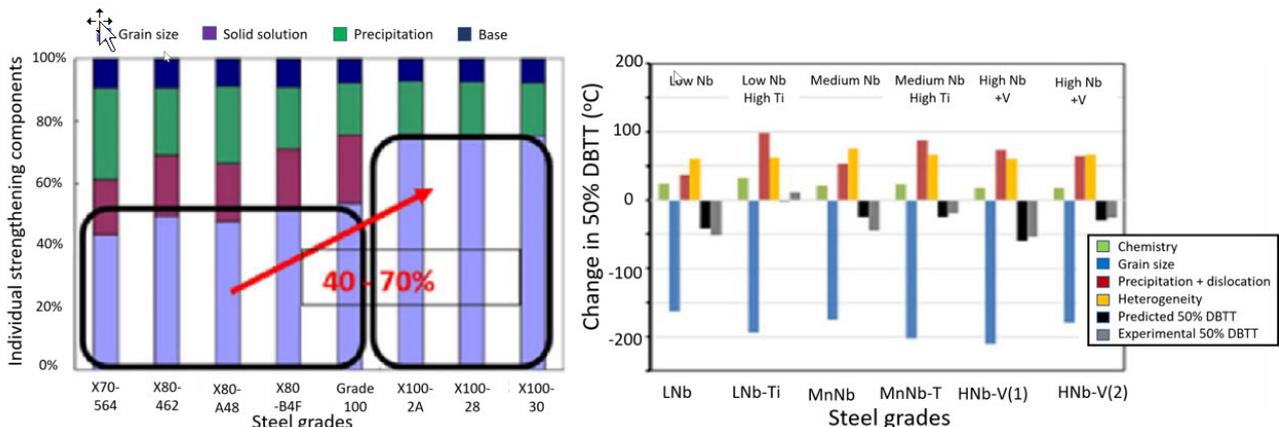
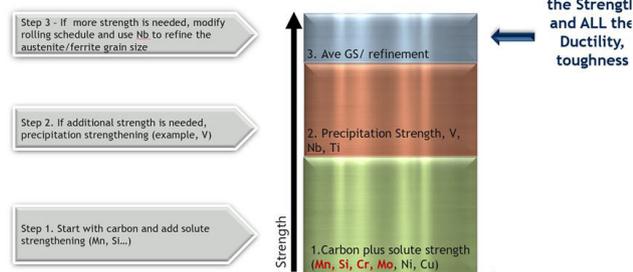


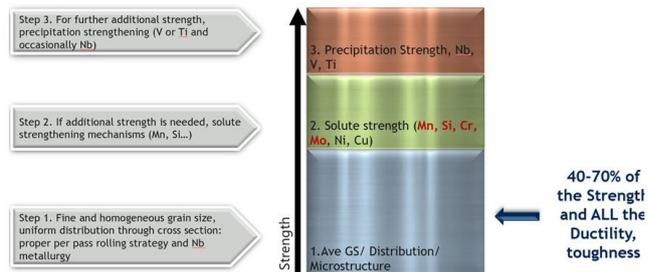
Figure 1. Strength and ductility components illustrated.

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



The outdated, conventional approach to alloy design

✦ Optimized approach to designing strength including ductility



A new, optimized cost-effective approach to alloy design

Figure 2. Illustration of outdated conventional vs. new optimized cost-effective approach to alloy design for strength and ductility.

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 [8,9]. Very few steel producers control the post rolling cooling in a way that would promote effective/optimum use of post rolling precipitation and hence results in variable stability of final mechanical properties, Figure 3, “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.

### 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 major, effect in developing that first metallurgical building block, i.e. Step 1 [10]. By utilizing even 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. For instance, consider the effect Mn the solution strengthening contribution to strength utilizing equations for YS and TS developed by Pickering, see Equation (2) below [11]. From these equations, the contribution of Mn to both YS and TS can be calculated, Table 1.

$$\begin{aligned} \text{YS} &= 53.9 + 32.3\text{Mn} + 83.2\text{Si} + 354.2\sqrt{\text{N}_{\text{sol}}} + \frac{17.4}{\sqrt{d}} \\ \text{TS} &= 294.1 + 27.7\text{Mn} + 83.2\text{Si} + 2.85 \text{ Pearl} + \frac{7.7}{\sqrt{d}} \end{aligned} \quad (2)$$

Table 1 shows that reducing the Mn content of 0.30 or 0.50 Mn only there is a contribution of 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 the 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  $\mu\text{m}$ , 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.

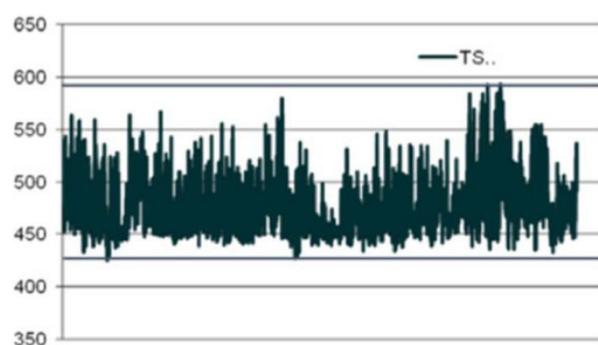
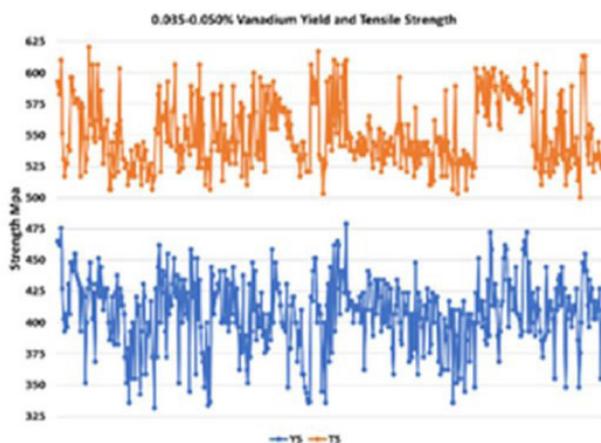
Recent research by Zhe [12] has shown that dilute amounts of Nb, even at rolling temperatures  $>950^\circ\text{C}$  can refine the austenite grain size, Figure 4. The Figure shows that at  $1000^\circ\text{C}$  a dilute Nb addition of 0.010% can reduce the austenite grain size from 80  $\mu\text{m}$  to 60  $\mu\text{m}$  resulting in a potential 2  $\mu\text{m}$  (16  $\mu\text{m}$  to 14  $\mu\text{m}$ ) 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

**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             |

YS and TS here mean yield and tensile stresses respectively.



**Figure 3.** Examples of YS and TS of V and Ti post rolling production precipitation strengthening stability due to lack of post rolling cooling process control.

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 5 [13].

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 5. 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 the 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.

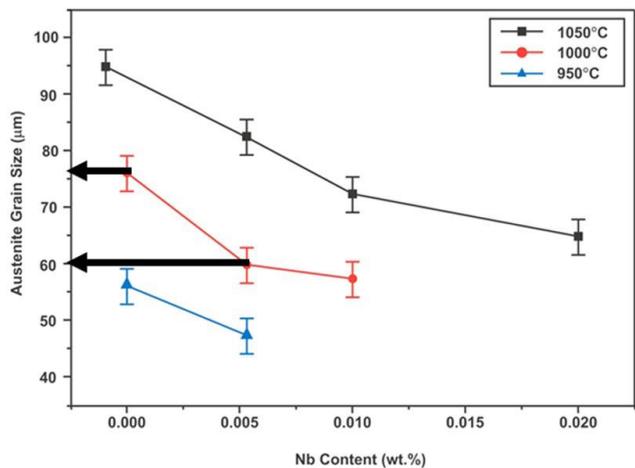
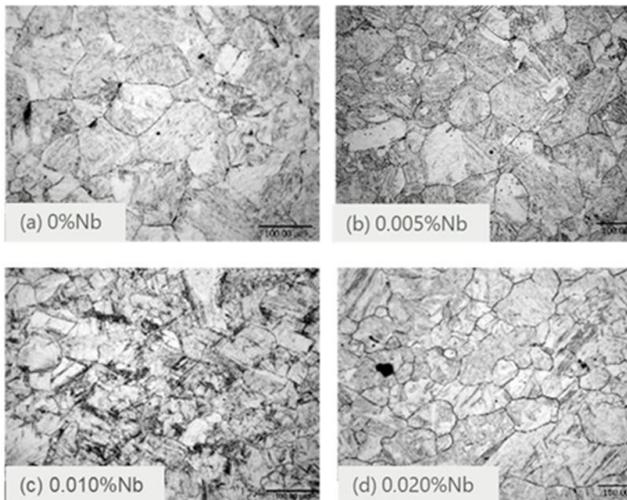


Figure 4. Austenite grain size evolution of 0.08% C steel after 20 second holding period at 1000°C followed by water quenching vs. Nb level.

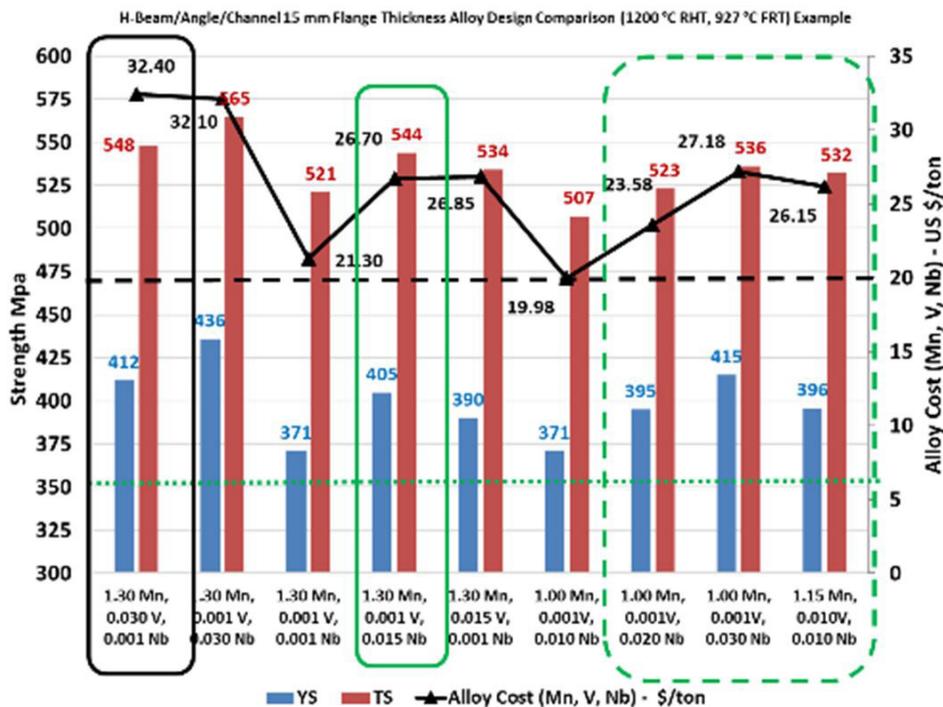


Figure 5. Example of alloy optimization modeled simulated strength possibilities for 15 H-beam considering Mn, V, and Nb. YS and TS here mean yield and tensile stresses respectively.

### 4 RESULTS AND EXAMPLES

Figure 6 shows examples of strengthening by two different mechanisms: post rolling precipitation and grain refinement. 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 7 shows examples of results obtained from a 0.50% Mn reduction with a dilute 0.010% Nb addition on mechanical properties and flatness at NISCO.

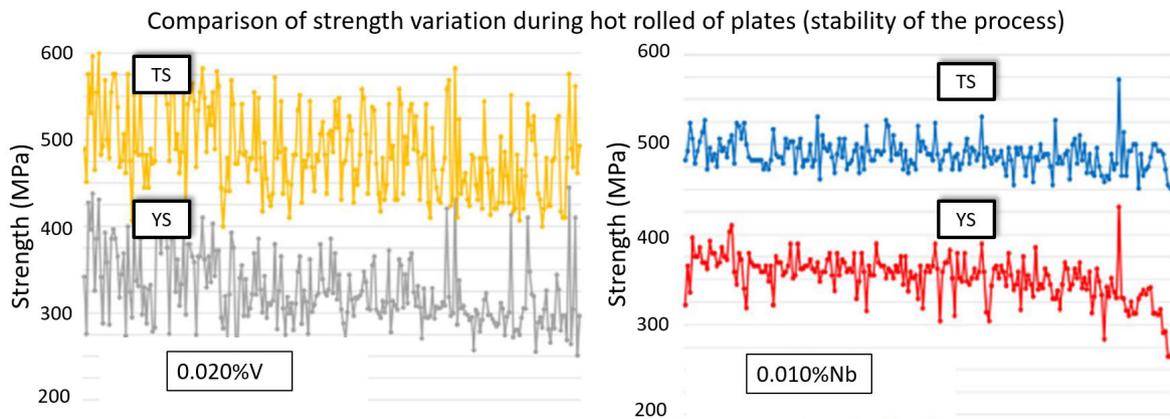
Minor changes in final ferrite grain size, as little as a 2 μm, is enough to allow for a 0.50% Mn reduction and still produce the same strength level. This concept was successfully implemented at Nanjing Iron and Steel (NISCO) in 2017 in structural steel 345 MPa minimum YS up to 40 mm in thickness. Strength and flatness requirements 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.

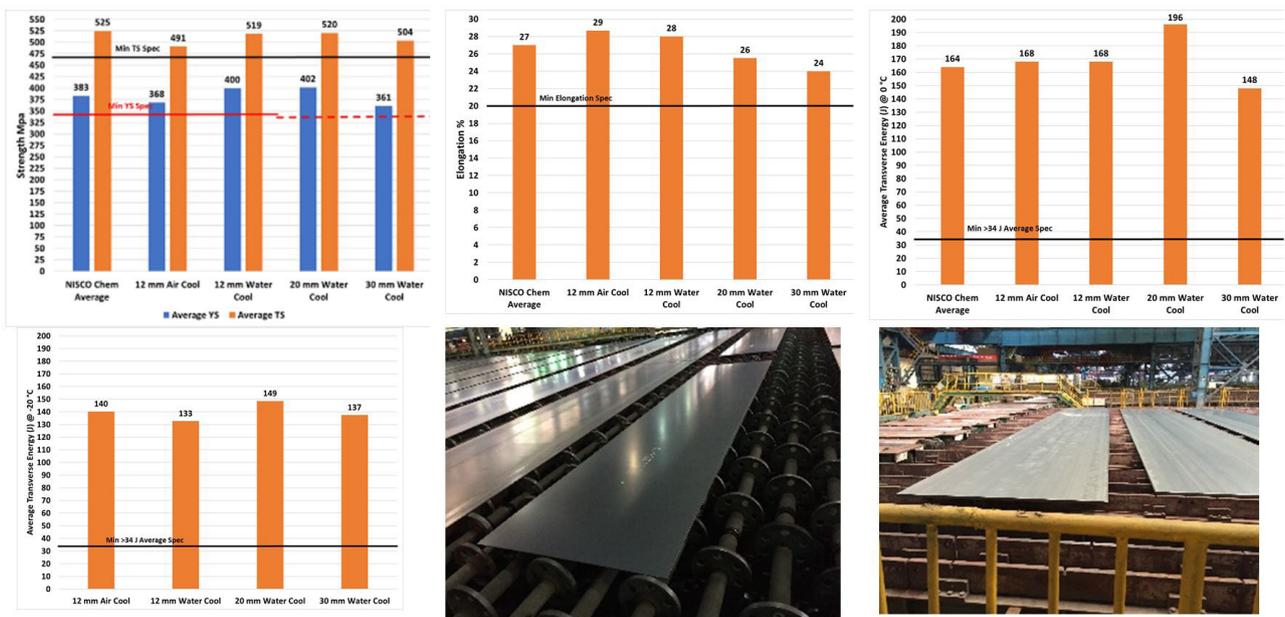
Figure 8 shows a comparison of microstructure and grain size for a 20 mm plate comparison of higher Mn no Nb and lower Mn with 0.010% Nb structural steel. Analysis of various strengthening components is also presented. Note the average ferrite grain size difference at the 1/4 and center thicknesses close to a 2 μm difference.

Figure 9 shows that there is an obvious improvement in slab centerline alloy segregation quality and corresponding microstructural banding.

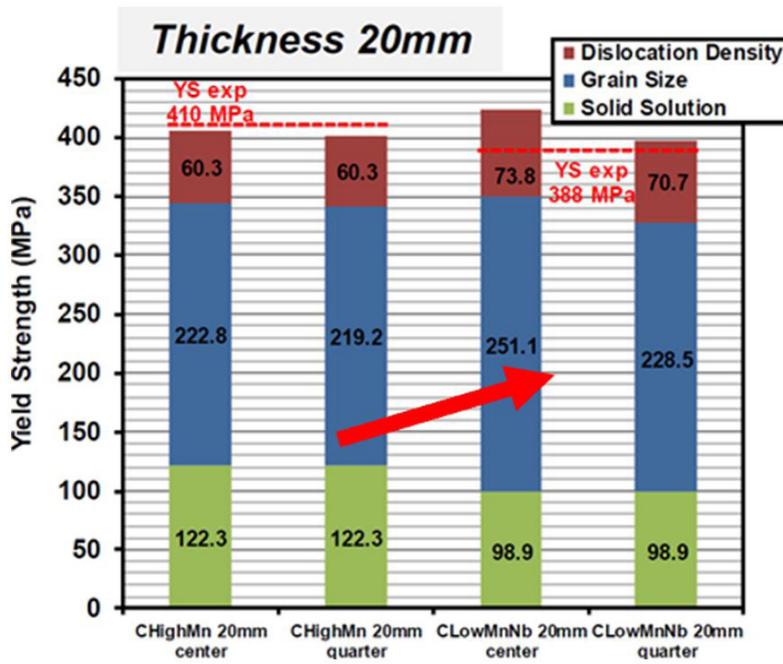
MicroSim® PM modeling of the austenite grain size evolution of the C/Higher Mn alloy design vs. the C/Lower Mn 0.010% Nb design also shows the same trends in the



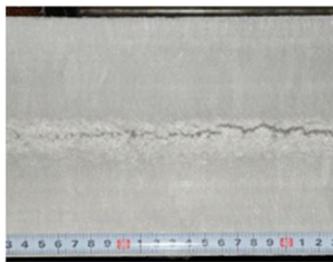
**Figure 6.** ASTM A572 Gr50 post rolling precipitation strengthening vs. austenite/ferrite grain size refinement strengthening comparison of V and Nb in hot rolled structural steel plate production. YS and TS here mean yield and tensile stresses respectively. Each represent mechanical properties obtained from a rolled industry run.



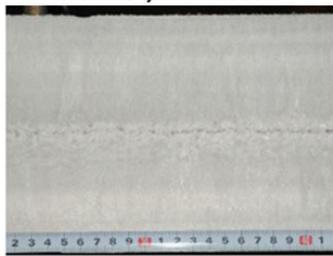
**Figure 7.** Examples of results obtained from a 0.50% Mn reduction with a dilute 0.010% Nb addition mechanical properties and flatness at NISCO.



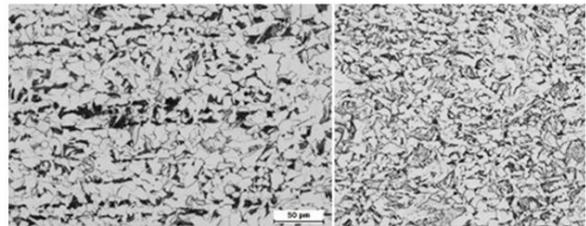
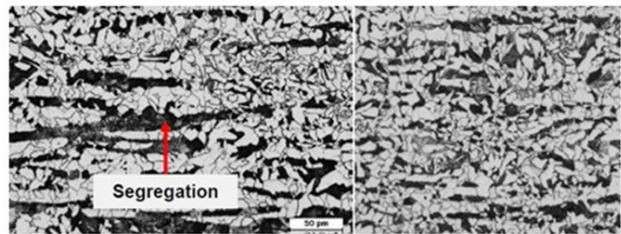
**Figure 8.** Comparison of microstructure and grain size for a 20 mm plate comparison of higher Mn no Nb and lower Mn with 0.010% Nb structural steel. YS and TS here mean yield and tensile stresses respectively.



**C-0.16%, Mn-1.30%**



**C-0.16%, Mn-1.05%**



**Figure 9.** Slab macroetch and microstructural banding comparison between higher and lower Mn.

austenite evolution. Modeling indicates an overall finer austenite evolution and better cross-sectional distribution at the end of the rolling process, Table 2. Figure 10 shows industry results in which addition of Nb replacing V improved mechanical properties in the case of H beams, and also decreased 2-sigma values, demonstrating better process control (case shown in rebars) [14].

Since the increase in FeMn costs starting in late 2016 and then FeV pricing increase/volatility starting in late 2017 there has been strong interest by many structural steel producers to optimize their alloy costs for Mn and V

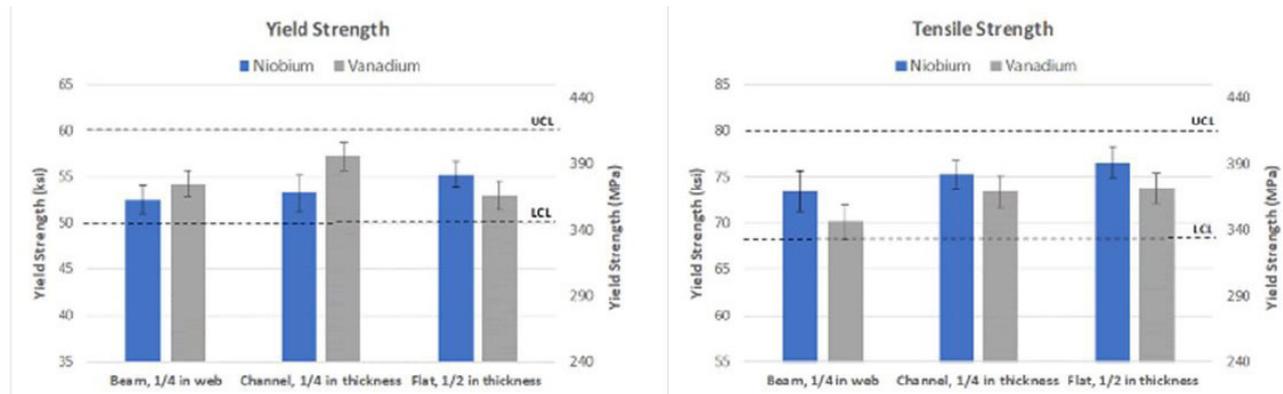
additions. This has been done in plates, hot strip, H-beams, angles and rebar around the world. In some cases, there is already a purposeful Nb addition, such as 0.010% that can be increased by 0.010% Nb to 0.020% Nb and then the Mn reduced by 0.30% or more allowing for USD \$1-2/ton of cost savings 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:

- a) Hot Strip – S355 up to 16 mm, Mn reduction with 0.010% Nb, Mn reduction V removed with 0.025% Nb;

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

|                                    | Average Austenite GS $\mu\text{m}$ | 90% Max Austenite GS $\mu\text{m}$<br>(Dc 0.10) | Maximum Austenite GS $\mu\text{m}$ |
|------------------------------------|------------------------------------|---|------------------------------------|
| <b>0.16%C/ 1.40% Mn</b>            | 23                                 | 73  | 254                                |
| <b>0.16%C/ 0.90% Mn/ 0.010% Nb</b> | 18                                 | 50  | 192                                |

GS means Grain Size and YS and TS are the yield and tensile stresses respectively. Dc 0.10 is the grain size value below which 90% of all grains in the sample are found.<sup>1</sup>



**Figure 10.** 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. YS here means the yield stress of the steel.

- b) Plate – S355, AH32/AH36, AH/DH36, SM490;
- c) H-beams/Angles – S355, A572 Gr50;
- d) Rebar – 400 MPa min YS.

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. Tools such as calibrated empirical physical prediction models and MicroSim<sup>®</sup> austenite evolution modeling can be used to properly optimize the alloy design and process parameters for the overall optimization of production costs of structural steels.

## 5 CONCLUSIONS

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

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