A New Cost Effective Metallurgical Design Strategy to Develop Optimized Strength and Ductility Properties in Structural Steels

Douglas G. Stalheim*
Ronaldo Barbosa**
Jose Rodriguez-Ibanez***
Marcelo Rebellato****
David Jarreta*****

Synopsis

Annually over 500 million tons worldwide of flat and long commodity grade structural steel products are produced for applications in the construction sector. Major costs to produce these commodity grade structural steels lies in alloys, energy and depending on region labor. Production costs for these commodity grades, which typically have low margins for profits, continue to rise worldwide driven by ferro alloy costs. Improved operational efficiencies (productivity, reduced energy consumption, improved melt to finished yields, reduced consumable consumption, etc.) can be realized along with lowered alloy costs with a proper understanding of a new metallurgical strategy to alloy design. These operational efficiencies along with cost savings can be accomplished with proper alloy design in conjunction with the mills processing capabilities to achieve the desired end metallurgy/mechanical properties. Requirements of strength and ductility for any given structural steel microstructure are obtained from three metallurgical mechanisms or “building blocks”: a) grain size refinement, b) solid solution and c) precipitation. Overall operation costs including alloy costs can be minimized if better engineering of these contributions can be realized. The correct use of these factors brings improved process/mechanical property stability. Use of practical metallurgical modeling tools along with mill data to determine process control capabilities can also assist in optimization of the metallurgical designs for cost effective structural steel production.

Keywords: Grain Size, Distribution, Niobium, Process Strategy, Metallurgy, Optimization

* Bachelor of Science in Metallurgical Engineering, South Dakota School of Mines and Technology, President, DGS Metallurgical Solutions, Inc., Vancouver, WA USA Consultant – CBMM Technology Suisse SA, Geneva, Switzerland

** Master and PhD, Sheffield University, England. Professor, Universidade Federal de Minas Gerais, Brazil.

*** Doctor in Mechanical Engineering, Univ of Navarra President, Ceit Research Institute, San Sebastian (Spain) Professor, Tecnun Engineering School, Univ. of Navarra, San Sebastian (Spain)

**** Bachelor of Science in Metallurgical Engineering, FEI – Brazil Euro- RMS Rolling Mill Solutions, Sao Paulo - Brazil Consultant – CBMM Technology, Sao Paulo – Brazil

***** Consultant, CBMM Technology Suisse S.A., Geneva, Switzerland Managing Director, Metal Prime Technology Pte Ltd, Singapore
Introduction

Flat and long product commodity grade structural steels used in the construction sector represent approximately over 500 million annual tons worldwide. Alloys along with energy and labor represent major costs in the production of structural steels. A proper understanding of alloy design to fit a given mill processing capabilities to achieve the required specification requirements will result in significant alloy and operational efficiencies. The main specification requirements of strength and ductility for any structural steel microstructure are obtained from three metallurgical mechanisms or “building blocks”: a) grain size refinement, b) solid solution and c) precipitation (1,2). Operational efficiencies along with overall reduction in alloy costs can be realized with a solid understanding on how to engineer the three metallurgical mechanisms/building blocks. Proper use of the metallurgical “building blocks” will reduce yield losses by bringing stability to the process and final mechanical properties. Implementation of practical tools utilizing the actual mill data and robust metallurgical modeling can assist in designing overall optimized cost-effective alloys for the production of structural steels.

Structural Steel Alloy Design Strategy

General

Mechanical properties for commodity structural steels are the driving force for proper design of cost optimized alloy strategies. The end use application or final shape for the structural steel (ship, building, plate, coil, H-beam, rebar, etc.) does not matter as the metallurgical strategy will be similar. Mechanical properties for these steels are typically have yield and tensile strength requirements in the 235-420 MPa and 370-520 MPa respectively with most of the production tons of these structural grades in the 235-355 MPa minimum yield strength range. Elongation requirements are typically ≥ 20% with typical charpy toughness when required at an average minimum of 34 J @ +20 °C, 0 °C or -20 °C depending on grade. The typical base microstructure of a predominately polygonal ferrite with a volume fraction of pearlite ranging from 5-20% depending on carbon content is used to meet the mechanical properties. The base alloy design for these commodity structural steels is carbon in the range of 0.05-0.25%, manganese in the range of 0.90-1.60% and silicon in the 0.10 – 0.40% range. Microalloying additions of vanadium, niobium and titanium may or may not be added depending on the grade, but typically not added in strength ranges up to and including 355 MPa minimum yield strength. Processing is either hot rolled or controlled roll (control of finish rolling temperature) regardless of the shape and can be followed by either air or water post rolling cooling.

Main Metallurgical Building Blocks for Strength and Toughness

If has been well established in structural steels that the three main “building blocks” for generating strength are:

- Grain size refinement
- Solid solution strengthening
- Post rolling precipitation strengthening
Ferrite grain size can contribute 40-70% of the total strength for a given microstructure in structural steels and **ALL** the toughness and represents the most effective and less costly approach to strength and toughness, **Figure 1**. This is accomplished through proper austenite grain conditioning during hot rolling by optimization of key processing parameters.

**Figure 1** illustrates that the other two building blocks for strength, solid solution and post rolling precipitation strengthening contribute to strength but to a much lesser degree and negatively affect toughness. From experience, post rolling precipitation strengthening, primarily using vanadium or titanium while easy to control in the laboratory is not so easy or efficient to control in the post rolling production environment and hence typically requires levels in the 0.030-0.100% range or more to achieve the desired strength. The challenge in optimizing and making precipitation strengthening an effective approach is related to the type of process control that is required in production to assure the proper final precipitate size, smaller is better, and volume fraction, larger is better as defined by the Ashby-Orowan relationship where “f” equals volume fraction of precipitate and “x” equals the average diameter of the precipitate, **Figure 2**. (3)

\[
\Delta \sigma_{ppt} = \frac{5.9}{x} \sqrt{f} \ln \left( \frac{x}{2.5 \times 10^{-4}} \right)
\]

**Figure 2** – Ashby-Orowan relationship for determining YS contribution from precipitation strengthening mechanisms.
There are two methods that create strength through post rolling precipitation, interphase and random. Interphase is the most effective, but very difficult to achieve in the production environment and hence has significant limitation for implementation. Random precipitation is the most common method implemented in production upon final plate/coil/bar/H-beam cooling but is less effective and overall inefficient due to lack of proper process control utilized by most steel production facilities. Unfortunately, this strengthening methodology requires that a significant volume of either V or Ti still in solution upon entry to the post rolling cooling phase that could potentially precipitate which typically is an unknown and is dependent on prior processing parameters and in some cases such as Ti going all the way back to the LMF process in steelmaking. Then the post rolling cooling parameters need to be understood and properly controlled for either interphase or random precipitation to occur and to be cost-effective, Figure 3. (4, 5)

![VN Interphase Precipitation](image1) ![VN Random Precipitation](image2) ![TiC Interphase Precipitation](image3) ![TiC Random Precipitation](image4)

V interphase/random precipitation temperature regime

Ti interphase/random precipitation temperature regime

Fig. 3 – Examples of V and Ti precipitation strengthening mechanisms time/temperature range

The challenges related to production process control or implementation for precipitation strengthening as a strengthening mechanism can also result in varied stability of final strength properties. However, when using microalloying, primarily Nb, for grain size control during rolling improved stability can be realized. Figure 4 shows hot rolled plate and coil production data with various levels of V, Ti and Nb. The strengthening mechanism for the V and Ti examples comes from post rolling precipitation strengthening mechanisms, while the strengthening mechanism in the Nb examples comes from austenite grain size control during hot deformation.
Hot rolled plate with 0.035-0.050% V for precipitation strengthening

Hot rolled coil with 0.040% Ti for precipitation strengthening

Hot rolled plate with 0.010% Nb for austenite grain size control and corresponding strengthening

Hot rolled coil with 0.020% Nb for austenite grain size control and corresponding strengthening

**Fig. 4**– Example of production strength variability of hot rolled V and Ti precipitation strengthened structural steels vs. hot rolled Nb austenite grain size control and corresponding strengthening

With increasing costs of ferro-alloys today, **Figure 5**, using solid solution and precipitation strengthening mechanisms are becoming a less cost-effective approach to strength for commodity grade structural steels. New/different strategies are needed to produce these structural steel grades cost effectively.

**Fig. 5** – HiC FeMn and FeV worldwide pricing trends since April 2016 to March 2018 (6)

Historically, traditional building blocks for metallurgical strategy for structural steels to develop strength with very little consideration for ductility consisted of the following strategy:

1. Carbon base plus solute strengthening with Mn, Si, Cr, Mo, Ni or Cu
2. Post rolling precipitation strengthening, primarily with V
3. Austenite/ferrite grain size refinement

**Figure 6** illustrates this historical traditional metallurgical strategy building block approach.
Step 1 – start with carbon and add solute strengthening mechanism elements as needed, typically Mn, Si, Cr or Mo

Step 2 – If additional strength is needed use post rolling precipitation strengthening mechanism typically using random precipitation from V

Step 3 – If additional strength is still needed then modify the rolling schedule and use some Nb to refine the austenite/ferrite grain size

Step 3 is where ALL the ductility would come from plus stability of strength properties over production runs.

Fig. 6 – Traditional metallurgical strategy building block approach to mechanical properties

This traditional metallurgical building block strategy approach to strength and toughness is not optimum for stable metallurgy/mechanical properties nor these days the most cost-effective use of ferro alloys. Therefore, a new/proper metallurgical building block approach strategy for optimized development of strength and toughness is needed. This new strategy for any structural steel grade starts with designing the alloy/processing in a cost-effective way to generate the finest and most homogenous cross sectional final ferrite grain size as possible for a given microstructure. Then if additional strength is needed then cost-effective additions of Mn, Si, Cr, Mo, Ni or Cu can be made. If even more strength is needed, then and only then should one rely on post rolling precipitation strengthening mechanisms typically using V or Ti for the increased strength. Microstructural requirements for the grade, predominately bainitic or martensitic microstructures, will preclude from post rolling precipitation strengthening mechanisms as an option for strength. While there are three building blocks to create strength, there is only ONE building block, building block #1 average GS and uniform cross-sectional distribution of the grains, that contributes to ductility properties (toughness, formability, elongation, etc.) for a given microstructure. Figure 7 illustrates the new/proper metallurgical building block strategy for cost effective strength and ductility for structural steels.

Fig. 7 – The new/proper building block metallurgical strategy for cost effective alloy designs for structural steels.
In fact, the first two building blocks of grain size/distribution and solute strengthening, if done correctly, can contribute to up to almost 500 MPa YS and with proper rolling to create some dislocation density that strength can be further increased to almost 600 MPa without the need of any post rolling precipitation strengthening mechanisms, Figure 8.

**Fig 8. – Example of achievable YS with only grain size and solute strengthening mechanisms.**

**Alloy design strategy for cost-effective metallurgy/mechanical properties**

Most commodity structural steel grades consist of three main starting elements, C, Mn and Si with very little else for alloy. In most cases Mn is the element that represents the largest weight percentage in the alloy design has become a rather costly alloy addition over the past two years. While developing a cost-effective alloy design we can use the equations by Pickering, Figure 9 (7), to determine how much the Mn contributes to YS and TS. In addition, it should be noted that Mn modifies the austenite to ferrite transformation temperature, $A_{r3}$, which has an indirect effect on the final ferrite grain size which is difficult to quantify. The Pickering equation can conversely show us how much YS and TS can be realized from the average ferrite grain size.

A typical S355 structural plate with a typical 0.16% C, 0.25% Si may have a 1.40% Mn level. However, to optimize cost effectiveness the Mn level might be able to be reduced to the 0.90% level. Based on the Pickering equation, the Mn difference of 0.40% is only equal to approximately 13 MPa yield strength and 11 MPa tensile strength. To compensate for the approximate reduction in strength of 13 MPa YS and 11 MPa TS due to the solute strengthening effect of the Mn, we can look on the other side of the Pickering equation at the average ferrite grain diameter contribution to strength. If the final average ferrite grain size can be reduced from 15 µm to 13 µm, only a 2 µm reduction in average ferrite grain size, based on the Pickering equation 11 MPa YS and 5 MPa TS can be realized, making up for most of the strength change seen from a significant reduction in the Mn. If that average ferrite grain size is further reduced by an additional 1µm to 12 µm, then the YS will be 17 MPa and TS 8 MPa. This minor change in final average ferrite grain size will then result in all the YS and most of the TS reduction due to the change in Mn to be fully recovered.
To achieve such a change in final ferrite grain size can be influenced by a micro addition of Nb, 0.005-0.020%, that can assist in austenite conditioning during hot deformation. While higher levels of Nb, >0.020% and its effect on austenite/ferrite final average grain size is well documented, there is limited research on micro additions of Nb <0.020%. Recent research has shown that even Nb levels as little as 0.005% can influence austenite grain evolution. Figure 10. (8) Well established work by Siwecki, et.al. and others shows that by increasing the austenite interfacial area per unit volume ($S_v$) results in a finer transformed ferrite grain size, Figure 11. (9) Minor changes in austenite grain size from 80 µm to 60 µm with 0.010% Nb at 1000 °C, Figure 10, can result in a 2 µm change, Figure 11, in the final ferrite grain size contributing to the strength seen from the Pickering equation.

Fig. 10 – Austenite grain size evolution of 0.08% C steel after 20 second holding period at 1000 °C followed by water quenching vs. Nb level

Fig. 11 – As seen in Figure 10 at 1000 °C a micro 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.
Either or a combination of solute drag and/or strain induced precipitation of the small Nb addition can result in what is observed in the austenite grain size at hot rolling temperatures. Practical models such as MicroSim® can be used to determine the mechanism at work. **Figure 12** shows actual production data from 20 mm C (0.16%), Mn (0.90%), micro Nb (0.010%) vs. C (0.16%), Mn (1.43%), no Nb S355 structural steel plate with normal rolling followed by light post rolling ACC cooling. Using MicroSim® modeling illustrates that solute drag is a predominate recrystallization mechanism throughout the rolling schedule in the micro Nb alloy design. The result is an average final austenite grain size of 17.9 µm for the micro-Nb alloy design vs. 23.1 µm for the no Nb alloy design. In addition, the maximum final austenite grain size along with 90% of the austenite grains (Dc(0.1)) are both significantly finer. As can be seen in **Figure 12** the YS are similar, the TS are very close to each either and elongation values are the same with all values easily meeting the specification requirements. It should be noted that a micro Nb addition while affecting the austenite grain refinement can also modify the phase transformation continuous cooling kinetics such to promote a small volume fraction of non-polygonal/acicular ferrite/bainitic phases to form which will also assist in increasing the strength.

**MicroSim® per pass austenite grain size evolution for 0.16% C, 0.90% Mn, 0.010% Nb, 20 mm S355 plate. Actual YS – 402 MPa, TS – 520 MPa, Elongation – 26%**

**Fig. 12** – Example of MicroSim® modeling to show the main recrystallization behavior, green box, and corresponding final austenite grain size, red box, that drives the strengthening mechanism for two distinctly different Mn/Nb alloy designs.

**Alloy Optimization**

**Mn-Nb Alloy Optimization**

The following are actual production examples for hot strip and plate where a significant cost savings was realized along with other important metallurgical benefits such as less as-cast segregation/microstructural banding and lower CE for weldability by optimizing the Mn with a micro-Nb addition, **Figure 13**. All rolling/cooling processing parameters were kept the same. Modifying the alloy design to optimize alloy costs and further optimization of the rolling process with the assistance of MicroSim modeling can result in further overall further improved austenite final cross-sectional grain size resulting in a finer cross-sectional ferrite grain size and a further enhancement of strength, **Figure 14**.
Hot rolled strip Mn reduction by 0.30% and 0.40% with micro-Nb addition of 0.010% for equivalent mechanical properties.

Hot rolled plate Mn reduction by 0.50% with micro-Nb addition of 0.010% for equivalent mechanical properties.

Based on January 2018 US HiC FeMn pricing and typical Nb pricing approximate cost savings would be between US $2.30 – 7.30/ton for the examples. With typical steel plant annual tonnages of these commodity grades in the 200,000 - 400,000 mT range, annual savings would be in the US $460,000 - $2.9 million range.

Fig. 13 – Actual production Mn alloy optimization with micro-Nb addition. Based on January 2018 US HiC FeMn pricing and typical Nb pricing approximate cost savings would be between US $2.30 – 7.30/ton for the examples. With typical steel plant annual tonnages of these commodity grades in the 200,000 - 400,000 mT range, annual savings would be in the US $460,000 - $2.9 million range.

Fig. 14 – 30 mm, S355, C/Mn/Nb Non-optimized vs. optimized rolling. Note the improvement in the average, maximum and Dc ((0.1), 90% grains are < Dc (0.1) in size) (red and green boxes) and the corresponding improvement in the strength contribution from 181 MPa to 209 MPa.

Additional benefits by reducing the Mn content can be seen in Figure 15.
Carbon higher Mn (1.40%) as-cast slab segregation and corresponding center thickness/quarter thickness microstructural banding in 20 mm plate

Carbon lower Mn (0.90%) as-cast slab segregation and corresponding center thickness/quarter thickness microstructural banding in 20 mm plate. Note the significant improvement!

CE differences for alloy designs shown in Figure 12.

Fig. 15 – Additional benefits to Mn alloy optimization with micro-Nb addition

Additional Alloy Optimization

The use of V for strength is driven by precipitation strengthening mechanisms in post rolling cooling which is easy to control in the laboratory but more difficult to control efficiently in the production environment. This can easily be seen in actual plate production data comparing YS and TS for a low strength commodity grade plate utilizing C/Mn/small V addition vs. that of C/Mn/micro Nb addition, Figure 15. The average strength for the two microalloy designs is similar but the 2σ standard deviation for the V only steel is two times that of the Nb steel, Table 1. The main reason for the stability using the micro Nb addition as discussed prior is that it works in controlling austenite grain size/distribution during hot deformation which is a much more stable and easier to control production process then post rolling cooling precipitation. Many steel plants around the world have implemented Nb levels in the 0.005-0.020% range for C/Mn commodity structural hot strip, plate and shapes (H-beams) due to the overall strength property stability seen in Figure 15 when using Nb.

Table 1: Plate production data comparisons of strength and 2σ standard deviation for V vs. Nb commodity structural steel alloy design

<table>
<thead>
<tr>
<th>Microalloy</th>
<th>Average YS MPa</th>
<th>Average TS MPa</th>
<th>YS Standard Deviation MPa</th>
<th>2σ YS Standard Deviation MPa</th>
<th>TS Standard Deviation MPa</th>
<th>2σ TS Standard Deviation MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.010% Nb</td>
<td>353</td>
<td>489</td>
<td>24</td>
<td>49</td>
<td>17</td>
<td>83</td>
</tr>
<tr>
<td>0.020% V</td>
<td>326</td>
<td>489</td>
<td>42</td>
<td>83</td>
<td>50</td>
<td>101</td>
</tr>
</tbody>
</table>
0.020% V production strength stability example  Equivalent 0.010% Nb production strength stability example

Fig. 15 – Plate production example of low strength commodity grade strength stability with different microalloy designs

Optimization of both Mn and V with Nb additions up to 0.030% for commodity structural grade coil, plates and shapes such as hot rolled H-beams can be done taking advantage of the new building block metallurgical strategy. Figure 16 shows empirical modeling of actual 15 mm hot rolled H-beam flange production alloy/strength where a typical H-beam alloy design of C (0.15%)/Mn (1.30%)/V (0.030%) is used as a base strength/cost level. Then through calibrated empirical modeling the Mn and V are modified with various combinations of Nb and the corresponding strength and costs can be seen. It can easily be seen that similar strengths by replacing 0.030% V with 0.015% Nb results in similar strength levels and based on March 2018 ferro alloy costs a savings of US $15.60/mT. Further optimization by reducing Mn to 1.00% with either 0.020% Nb or 0.030% Nb further reduces alloy costs by US $19.62/mT or US $16.12/mT respectively compared to the initial starting base cost C/Mn/V alloy design. On 500,000 annual tons of S355 H-beam production this would be a significant cost savings in the USD $7.8-9.8 million range.

Fig. 16 – Empirical modeling of actual 15 mm hot rolled H-beam flange production alloy/strength with micro-Nb additions

Fig. 17 – Actual 15 mm H-beam flange production base alloy/strength empirical modeling of Mn/V alloy optimization with micro-Nb additions
Conclusions

With increasing ferro alloy costs, production of commodity grade structural steels is resulting in cost pressures. However, utilizing the proper metallurgical building block strategies for strength and ductility for a given microstructure where the focus should be in achievement of as much strength from the grain size/distribution followed by solute strengthening mechanisms and then finally if needed post rolling precipitation strengthening mechanisms alloy costs can be optimized. Use of practical models such as MicroSim® and good empirical models utilizing actual production data in each case can be tools to assist in optimization of the alloy/rolling design so that alloys can be properly optimized to reduce overall alloy costs. Several examples shown opportunities for production of cost-effective stable commodity grade structural steels has been discussed.

References