HIGH STRENGTH STEEL AS A SOLUTION FOR THE LEAN DESIGN OF INDUSTRIAL BUILDINGS

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Abstract

This paper presents the actual case of an industrial building at CBMM's plant in Araxá, Brazil as an example of lean design using microalloyed steels. The structure was made mostly with microalloyed ASTM A572 steel instead of the traditional carbon manganese ASTM A36 steel. This paper provides a metallurgical evaluation of the microstructures of both steel types together with their respective mechanical properties.

The effect of niobium, which promoted increased strength and toughness simultaneously, allowed a 22% saving in total steel consumption within this project. Cost reduction and benefits in energy and CO_2 emissions are demonstrated.

Introduction

Structural steel is known worldwide as a solution for important challenges faced in the construction of buildings. To achieve higher economic efficiency, there is a strong demand to build faster while lowering energy and raw material consumption. Furthermore, environmental awareness has led to the recognition that carbon dioxide emissions need to be reduced continuously. Due to this reality, structural steels are increasingly being used in modern construction.

Among steel families, microalloyed steels are the solution for designing leaner structures. Advances in metallurgy, involving microalloying and thermomechanical controlled processes, over recent decades have led to steel grades with higher strength and improved overall properties for structural applications that provide a superior answer to current challenges. Microalloyed structural steels are being increasingly employed in building construction, resulting in leaner structures and faster construction with lower raw material demands and reduced carbon dioxide emissions.

High strength microalloyed steels are steels whose properties have been modified by adding a small amount of an alloying element (usually less than 0.10%). Niobium is the solution when both increased strength and improved toughness are required. The economic benefits associated with using such small additions that confer significant improvements to mechanical properties have led to the growing popularity of microalloyed steels in the market.

This paper presents an actual case of 22% savings in total steel consumption, with an optimized engineering solution, for CBMM's new sintering plant in Araxá, Minas Gerais – Brazil, using niobium steel technology for the structural beams, plates and welded shapes. Costs and environmental benefits are also presented.

Strengthening Mechanism of Niobium Microalloying

Niobium effectively controls the microstructure of steel and small amounts of this element can refine the grain size of rolled products. The effects of niobium as a microalloying element are schematically illustrated in Figure 1 [1] for re-heating temperatures up to 1200 °C.

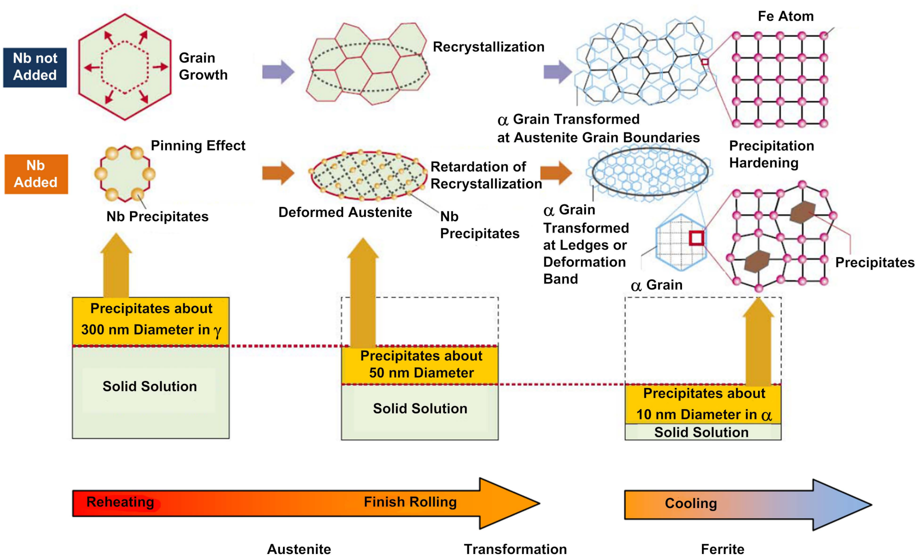


Figure 1. Niobium precipitation at each stage of heating, rolling and cooling and its effect on refining ferrite grains and precipitation hardening [1].

Achieving Higher Strength

Fine grain size is an essential requirement for steels to obtain improved strength and toughness properties. Figure 2 [2] shows the large effect that grain size (d) has on mechanical yield strength (σ_y) in carbon-manganese steels.

Reducing grain size generates a robust increase in strength for all carbon contents considered. The increase is even more marked with niobium microalloying due to its effect of preventing recrystallization during controlled rolling. Additionally, niobium precipitates as very fine particles, further contributing to increased strength.

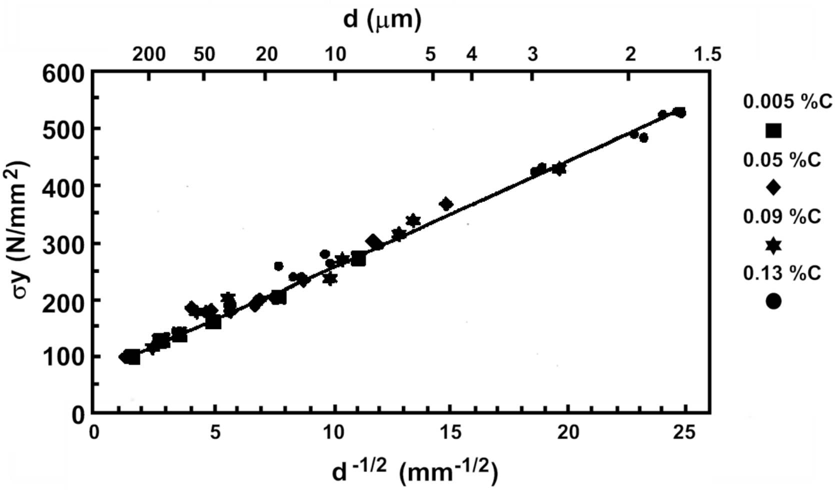


Figure 2. Relationship between grain size and yield strength.

High Strength and Increased Toughness Simultaneously

A study of ASTM 992 beams (S355), based on industrial heats, led to the commercialization of low-carbon niobium-bearing beams in place of vanadium-bearing beams [3]. The addition of niobium refines the grain size which increases strength and improves toughness. Near-net-shape cast structural beams containing niobium exhibit double the impact toughness at room temperature compared to a vanadium microalloy system at similar carbon, sulfur, phosphorous and nitrogen levels and cooling rates as illustrated in Figure 3.

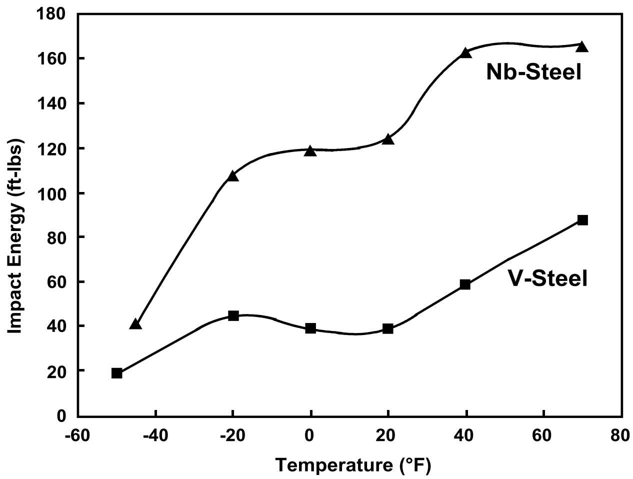


Figure 3. Charpy V-notch impact toughness comparison – niobium versus vanadium [3].

Objective

This paper presents the case of a steel framed industrial building at CBMM's plant in Araxá, Brazil as an example of lean design using microalloyed steels. The structure was made mostly with microalloyed ASTM A572 steel instead of the traditional carbon ASTM A36 steel. The objective was to show the advantages of using niobium microalloyed steel instead of carbon-manganese grades for lean structures.

Building Description

The sinter plant building, known as Sinter Plant II, is part of a project to increase the FeNb production capacity of CBMM's plant to 150,000 tonnes annually. The structure was fabricated and built in ten months in 2011 by CODEME Engenharia, a leading Brazilian construction company specializing in steel structures.

Sinter Plant II houses a Dwight Lloyd type sintering machine that produces niobium oxide sinter. The equipment installed in the building includes raw material bins and machinery for size classification and crushing. The production process requires an intense flow of materials on vertical and horizontal levels. As a result of the process performed at Sinter Plant II, niobium oxide sinter is delivered internally to the correct composition and particle size to manufacture niobium final products.

A building 28.5 m tall, 55 m long and 15 m wide was necessary to house the equipment for a production flow with vertical and horizontal processes.

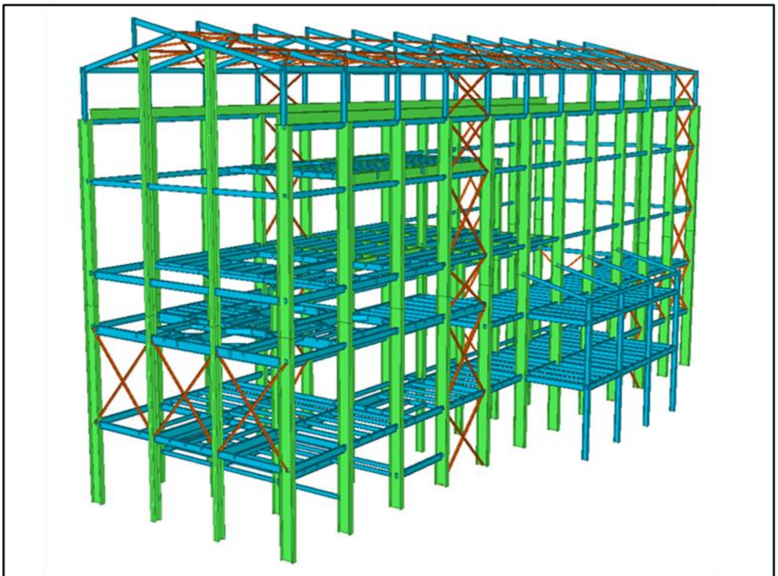
Building Evolution

Sinter Plant II is a structural steel braced frame building. The main structural components are composed of hot-rolled beams, plates and welded shapes made of ASTM A572 Grade 50 microalloyed steel, with hot-rolled shapes made of ASTM A36 carbon steel used for small structural elements such as bracing (Figure 5).

Figure 4 shows some of the steps in the construction of the building. Sinter Plant II began operations in August 2011.

Figure 4. Sinter Plant II; (a) Construction site and foundation, (b) View of columns and beams, (c) Lift crane installation, (d) Sinter Plant II general view.

The steel shapes and types used to build Sinter Plant II are presented in Figure 5. The colors depict different steel grades and different shapes. The amount of each steel shape and type used to build the entire structure is also listed.



Legend	Shape Type		Steel Type	Weight (kg)
		H Welded shapes	ASTM A572 Gr. 50 Microalloyed steel	**156,809**
		W Hot-rolled shapes	ASTM A572 Gr. 50 Microalloyed steel	**104,282**
		Angles Hot-rolled shapes	ASTM A36 Regular carbon steel	**22,614**
Total amount of structural steel				**283,705**

Figure 5. Schematic view of structural elements and steel types used to construct Sinter Plant II.

Materials and Methods

Shapes and Grades

Table I shows the ASTM specification requirements for niobium microalloyed steels used in the project as compared to the less efficient carbon manganese steel, ASTM A36.

Table I. ASTM Standard Specifications

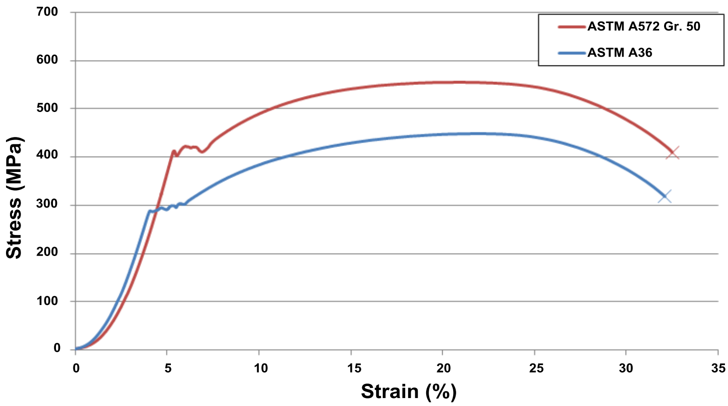
Standard Designation	Application	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Chemical Composition (wt.%)					
					C	Mn	Si	P	S	Nb
ASTM A 572 Grade 50	Welded Shapes	>345	>450	>21	<0.23	0.45-1.35	<0.40	<0.04	<0.05	0.005-0.05
ASTM A 572 Grade 50	Hot-rolled Shapes	>345	>450	>18	<0.23	0.45-1.35	<0.40	<0.04	<0.05	0.005-0.05
ASTM A36	Welded Shapes	>250	400-550	>20	<0.25	0.8-1.20	0.15-0.40	<0.04	<0.05	-
ASTM A36	Hot-rolled Shapes	>250	400-550	>20	<0.26	-	<0.40	<0.04	<0.05	-

Metallurgical and Mechanical Tests

To demonstrate and compare the characteristics of the niobium microalloyed steel and the conventional carbon manganese steel, 12 mm thick hot-rolled coil samples of both steels were evaluated using different tests. The test results are presented below.

Stress-strain Tests

A significant number of tests were performed for both steel types according to the ASTM A370 standard. Figure 6 presents examples of the stress-strain curves and results for the yield and tensile strength.



	ASTM A572 Gr. 50	ASTM A36
Yield Strength (MPa)	402± 12	289± 12
Tensile Strength (MPa)	555± 18	449± 18

Figure 6. Stress-strain curves for niobium microalloyed steel (ASTM A572 Gr. 50) and regular carbon manganese steel (ASTM A36).

The results show the superior properties of the niobium microalloyed steel in terms of yield strength and tensile strength. Results show that both materials achieve their specified ASTM standard requirements. It is also interesting to compare the area under both graphs. The larger the area, the tougher the material, and the higher its capacity to absorb energy before fracturing.

Impact Tests

Charpy impact tests were performed according to ASTM A370 and ASTM E23 at room temperature (26 °C) to evaluate the toughness of both steel types. Table II presents the results.

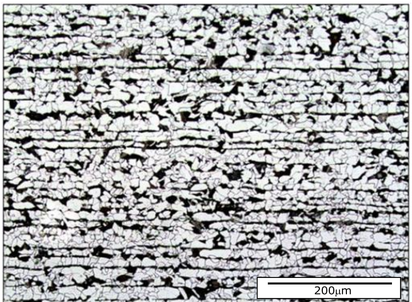
Table II. Absorbed Energy to Fracture in Charpy Test

Samples	ASTM A572 Grade 50 Toughness (J)	ASTM A36 Toughness (J)
1st Test	179	105
2nd Test	155	111
3rd Test	169	108
Average Result	168	108

The better toughness results achieved by the niobium microalloyed steel (ASTM A572 Gr. 50) are consistent with the stress-strain curves and will be discussed in terms of microstructures below.

Microstructure Analyses

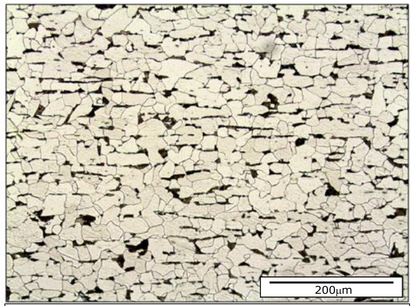
In order to show the differences in steel microstructure, samples of ASTM A572 Gr. 50 and A36 were analyzed. Figure 7 presents the results of the micrographic analysis.



Sample:
- Nb microalloyed steel ASTM A572 Gr. 50
- Hot-rolled - 12 mm thickness

Microstructure:
- Reagent Nital 2%
- Ferrite matrix with presence of oriented pearlite

Grain size:
- ASTM n. 8, equivalent approximately to a 22μm average grain diameter.



Sample:
- C Mn steel ASTM A36
- Hot-rolled - 12 mm thickness

Microstructure:
- Reagent Nital 2%
- Ferrite matrix with discrete presence of pearlite

Grain size:
- ASTM n. 6.5, equivalent approximately to a 38μm average grain diameter.

Figure 7. Micrographic analysis.

The lower grain size obtained in ASTM A572 Gr. 50 steel by niobium microalloying and proper thermomechanical processing is the main reason for the superior mechanical properties of this material, as presented above. If desired, a smaller grain size can be obtained by adjusting the thermomechanical process.

Building Design and Comparison Between ASTM A572 and A36

To evaluate the benefits of using microalloyed steels, the same building has been re-designed using only ASTM A36. This section evaluates the two different steel options:

Project A – actual building with a high strength steel structure (niobium microalloyed steel, ASTM A572 Gr. 50).

Project B – hypothetical building with a regular carbon manganese steel structure (lower strength steel, ASTM A36).

Calculation Method

Calculation standards and all requirements in terms of applied load, internal building area, volume, span, height, length and width were kept exactly the same in both projects.

It was considered that hot-rolled beams, plates and welded shapes of conventional carbon manganese steel ASTM A36 would be applied throughout in Project B.

The standard limits of yield strength, tensile strength, elongation and chemical composition for regular carbon manganese steel in both shapes of ASTM A36 presented in Table I were taken as the basis to calculate the requirements of the building with a regular carbon manganese steel structure.

In Project B (hypothetical building), each element of the building was calculated with the ASTM A36 standard yield strength to support exactly the same load as in Project A (actual building).

Based on the new dimensions and weight of each element and their assembly, it was possible to show the differences between the two projects.

Results

Dimensions

The hypothetical building (Project B) used regular carbon manganese steel. Due to reduced material strength, the majority of the main structural elements, such as beams and columns, had an increased size and transversal section area compared to the high strength steel building (Project A).

Figure 8 shows, in accurate scale, a comparison of superimposed shapes from the high strength steel framed building and the regular carbon manganese steel framed building. The superimposed shapes are able to resist exactly the same applied load.

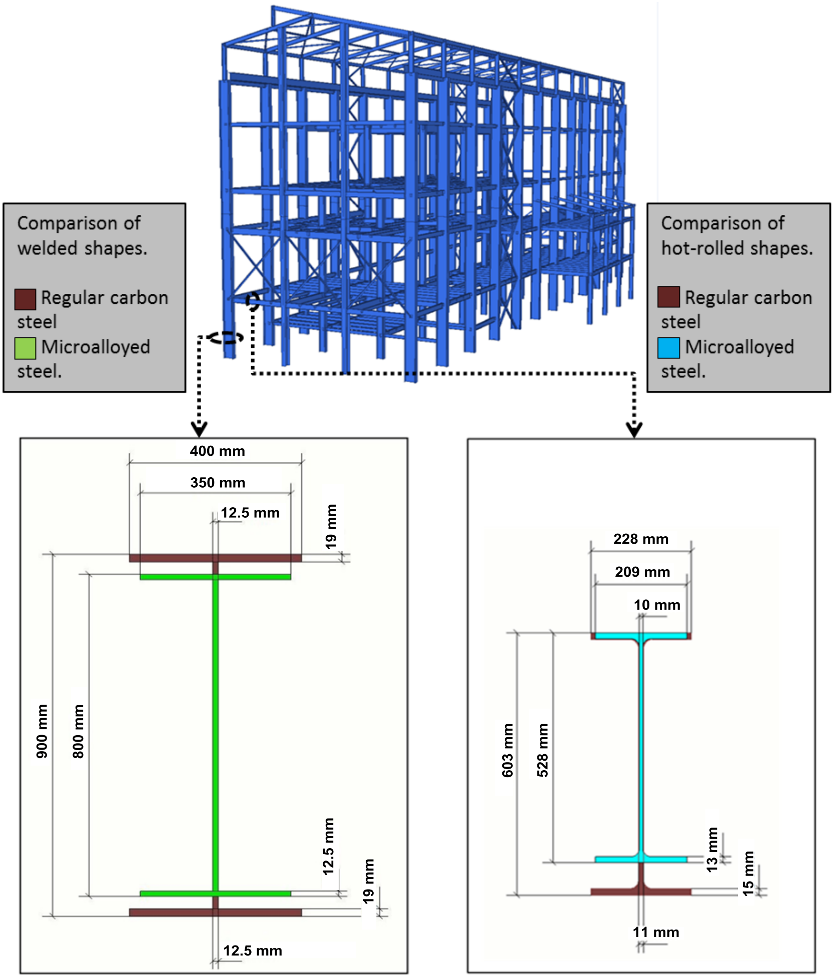


Figure 8. Comparison of the size of steel shapes made of regular carbon manganese steel versus high strength microalloyed steel.

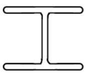
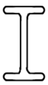
Weight

Table III shows the weight reduction in each type of structural element used in the actual building (Project A), compared to the carbon steel hypothetical building (Project B), while Table IV shows a comparison of the total weight of elements applied in both projects.

Table III. Steel Consumption Comparison by Element –
High Strength Steel versus Carbon Manganese Steel

Project A High Strength Steel (ASTM A572 Grade 50)		**Project B Regular Carbon Steel (ASTM A36)**		**Structural Element**	**Weight Reduction from B to A (%)**
Beam Shape Depth (mm) x Weight (kg/m)	**Linear Weight (kg/m)**	**Beam Shape Depth (mm) x Weight (kg/m)**	**Linear Weight (kg/m)**		
W310x44.5	44.5	W360x64.0	64.0	Beam	30
W200x26.6	26.6	W250x38.5	38.5	Column	31
W360x110.0	110.0	W610x155.0	155.0	Column	29
800x350/350x19.00/19.00x12.50	179.2	900x400/400x19.00/19.00x19.00	247.9	Column	28
800x350/350x12.50/12.50x12.50	144.7	900x400/400x19.00/19.00x12.50	203.9	Column	29
500x350/350x12.50/12.50x12.50	115.3	600x250/250x16.00/16.00x22.40	162.7	Column	29
500x350/350x16.00/16.00x12.50	133.8	600x250/250x22.40/22.40x22.40	185.5	Column	28
700x300/300x22.40/22.40x9.50	154.4	900x300/300x25.00/25.00x9.50	181.1	Beam	15
W150x18.0	18.0	W150x18.0	18.0	Beam	0
W250x44.8	44.8	W250x44.8	44.8	Beam	0
W410x75.0	75.0	W530x92.0	92.0	Beam	18
W530x92.0	92.0	W610x113.0	113.0	Beam	19
W610x113.0	113.0	W610x155.0	155.0	Beam	27
W530x82.0	82.0	W610x101.0	101.0	Beam	19
W410x60.0	60.0	W530x72.0	72.0	Beam	17
W200x19.3	19.3	W310x21.0	21.0	Beam	8
W360x44.0	44.0	W460x52.0	52.0	Beam	15
W250x25.3	25.3	W360x32.9	32.9	Beam	23
W410x53.0	53.0	W530x66.0	66.0	Beam	20
W310x28.3	28.3	W310x38.7	38.7	Beam	27
W310x44.5	44.5	W460x52.0	52.0	Beam	14
600x300/300x16.00/16.00x8.00	111.0	800x250/250x19.00/19.00x8.00	122.4	Beam for Crane Rolling	9

Table IV. Steel Consumption Comparison –
High Strength Steel versus Regular Carbon Manganese Steel

Structural Section		**Project A**	**Project B**	**Difference (kg) B-A**	**Difference (%) Reduction in Consumption Adopting Project A**
		Weight (kg) ASTM A572 Grade 50 High Strength Steel	**Weight (kg) ASTM A36 Regular Carbon Steel**		
	H Type – Welded Shapes	156,809	210,633	53,824	26
	W Type – Hot Rolled Beams	104,282	129,255	24,973	19
	L Type – Hot Rolled Beams	22,614	22,614	-	0
Total		283,705	362,502	78,797	22

By using high strength niobium microalloyed steel instead of regular carbon manganese steel to build Sinter Plant II, 22% less steel was used, representing a saving of 78.8 tonnes of steel.

Carbon Dioxide Emissions and Energy Consumption

Environmental sustainability is one of the foremost challenges facing steel companies around the world. The consumption of fossil fuels with its associated costs for coal, oil and natural gas, will continue to be a primary cost driver in iron and steelmaking. Carbon dioxide gas is generated in direct relation to the amount of steel produced.

Niobium microalloyed structural steels offer the opportunity to reduce the total weight of a given structure compared to a non-microalloyed steel construction.

Based on performed studies to analyze carbon dioxide emissions in a steel production chain [3], an evaluation was carried out to demonstrate the significant reduction in emissions (kg of CO_2) and energy consumption (GJ) by using high strength niobium microalloyed steel.

Figure 9 depicts the production flow used to manufacture the majority of the world's structural steels.

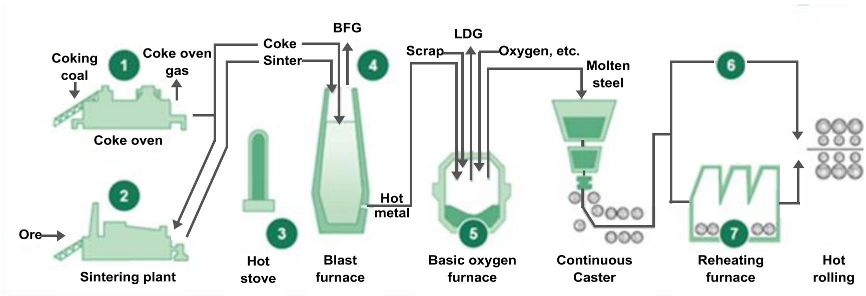


Figure 9. Example of the production flow for structural steels.

Tables V and VI present the reductions in carbon dioxide emissions and energy consumption achieved with a microalloying design. A 22% weight reduction with the microalloying design represents a decrease of 127,972 kg of carbon dioxide and energy savings of 1,779 GJ.

Table V. Carbon Dioxide Emissions

Production Line	**Reference**	**Project A (HSS)**	**Project B (Carbon Steel)**	**Reduction = B - A**
	CO_2 Emissions (kg/t Steel)	**Total CO_2 Emissions for 284 t Steel (kg)**	**Total CO_2 Emissions for 363 t Steel (kg)**	**Reduction in CO_2 Emission (kg)**
Coke Oven	51	14,512	18,549	4,037
Blast Furnace	1,000	284,000	363,000	79,000
BOF	245	69,495	88,826	19,331
Vacuum Degas/Ladle Metallurgy	39	10,962	14,012	3,049
Continuous Cast	20	5,623	7,187	1,564
Hot Rolling	189	53,534	68,426	14,892
Pickling	77	21,925	28,024	6,099
Total	1,620	460,052	588,024	**127,972**

For comparison purposes, an average European car that is driven 30,000 km per year generates 4,500 kg of carbon dioxide emissions. The reduction of 127,972 kg of carbon dioxide emissions achieved in Project A is comparable to the annual carbon dioxide emissions of 28 European vehicles [4].

Table VI. Energy Consumption

Production Line	Reference	Project A (HSS)	Project B (Carbon Steel)	Reduction = B - A
	Energy Consumption (GJ/t Steel)	Total CO_2 Energy Consumption for 284 t Steel (GJ)	Total CO_2 Energy Consumption for 363 t Steel (GJ)	Reduction in Energy Consumption (GJ)
Coke Oven	3.89	1,105	1,412	307
Blast Furnace	12.48	3,544	4,530	986
BOF	1.02	290	370	81
Vacuum Degas/Ladle Metallurgy	0.72	204	261	57
Continuous Cast	0.34	97	123	27
Hot Rolling	2.67	758	969	211
Pickling	1.40	398	508	111
Total	22.52	6,396	8,175	**1,779**

The energy saved using high strength steel compared to carbon steel in the construction of an industrial building was 1,779 GJ, representing a 21% gain in energy efficiency. To provide perspective on this saving, the annual per capita energy consumption in the United States is 338 GJ [5].

Cost

A cost comparison between the two steel options was made considering the total amount of steel used in construction and the supply price of the steel types.

The data above demonstrated that 22% less high strength steel was used compared to a regular carbon steel. However, the former costs 6% more per kilogram than the latter. Table VII shows a cost comparison of the two steel types considering both the weight reduction and the increased cost per unit.

Table VII. Cost Comparison

Steel Type	Total Weight (%)	Steel Unit Price (%)	Total Cost (%)
ASTM A36 – Regular carbon steel	100	100	100
ASTM A572 Grade 50 – High strength steel	78	106	83
Saving by adopting high strength steel			**17**

A saving of 17% in total steel costs was achieved by adopting the high strength steel instead of the regular carbon steel.

Conclusions

This paper illustrates the benefits of using high strength niobium microalloyed steel instead of a conventional carbon manganese steel for the construction of an industrial building to house CBMM's Sinter Plant II in Araxá, Brazil.

The finer grain size obtained in the niobium microalloyed steel led to a significant improvement in strength and toughness properties, compared to the conventional steel: Yield strength increased by 39%; tensile strength increased by 23%; Charpy toughness at 26 °C increased by 55%.

The main advantages of using the niobium microalloyed steels were:

- <u>Weight reductions and cost benefits</u>: By adopting the high strength niobium microalloyed steel, 22% less steel was used in the construction, a saving of 78.7 tonnes. The economy in steel volume/weight generated a reduction of 17% for the project's total steel costs;

- <u>Carbon dioxide emissions</u>: The niobium microalloyed steel solution prevented around 130 tonnes of carbon dioxide emissions. This benefit was a direct consequence of the lower amount of steel needed to complete the building project compared to the amount that would have been necessary if a conventional carbon steel were employed;

- <u>Energy consumption</u>: Due to the lightweight design made possible by using the high strength steel, less steel was necessary to construct the building. If a conventional carbon steel had been used, approximately 1,800 GJ of additional energy would have been required to produce the equivalent amount of regular carbon steel necessary to build the structure.

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