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TOOLS FOR THE DEVELOPMENT OF ALLOY DESIGNS FOR HOT ROLLED FLAT STEEL PRODUCTS

Antonio Augusto Gorni (1)
Marcelo Arantes Rebellato (2)
Danilo Di Napoli Guzela (3)

ABSTRACT

The permanent and diversified pressures exerted on steel mills – in terms of costs, availability of raw materials, carbon footprint and quality of final products – are making difficult to develop new alloy designs for steels. In view of this situation, digital tools were created to quickly evaluate the design of structural steels. Such applications, based on chemical composition and on the refining and rolling process data of structural steels, determine their final mechanical properties, as well as make a preliminary assessment of their suitability for the secondary refining process, continuous casting and welding, sensitivity to hot cracking, carbon footprint and costs. The use of such tools allows to accelerate the development of new steels and harmonize the potentially conflicting circumstances related to the manufacture and application of steel flat products.

Key words — HSLA Structural Steel; Niobium; Carbon Footprint; Alloy Design.

RESUMO

As permanentes e diversificadas pressões exercidas sobre as usinas siderúrgicas – em termos de custos, disponibilidade de matérias primas, pegada de carbono e qualidade dos produtos finais – estão tornando cada vez mais difícil a definição de projetos de liga para aços. Tendo em vista essa situação, foram criadas ferramentas digitais para avaliar rapidamente o projeto de aços estruturais. Tais aplicativos, a partir dos dados de composição química e do processo de refino e laminação de aços estruturais, determina as suas propriedades mecânicas finais, bem como faz uma avaliação preliminar de sua adequação ao processo de refino secundário, lingotamento contínuo e soldagem, sensibilidade ao trincamento a quente, pegada de carbono e custos. O uso dessas ferramentas permite acelerar o desenvolvimento de novos aços e efetuar harmonização entre as circunstâncias eventualmente conflitantes relativas à fabricação e aplicação dos produtos planos de aço.

Key words — Aço ARBL Estrutural, Nióbio, Pegada de Carbono, Projeto de Liga.

(1) Materials Engineer, M.Sc., Ph.D., Consultant, Brazil, antonio.gorni@gmail.com.
(2) Metallurgical Engineer, Consultant, RMS – Rolling Mill Solutions, Brazil
(3) Metallurgical Engineer, Consultant, Brazil

1. INTRODUCTION

In principle, the alloy design of a steel, that is, its combination of alloying elements, must guarantee that its specified properties and characteristics are met, and in the most economical way possible. But other requirements must also be satisfied. For example, the steel refining, forming and processing steps at the plant should be as simplified, economical and consistent as possible. The availability of the corresponding ferroalloys on the market, as well as the value and stability of their quotations over time, are also a crucial factor to be considered. Finally, the issue of sustainability is assuming significant importance, particularly regarding the resulting carbon footprint and recyclability of steel.

CBMM is developing several digital applications based on Microsoft Excel in order to rationalize the process of alloy design of microalloyed structural steels. One of them, *Alloy Design Otimization* (*ADO*), analyzes alloy costs, steelmaking and rolling technical aspects and final product mechanical properties. The other one, *ecoNb* [1], is more specific to steelmaking aspects, but it also calculates the Global Warming Potential (GWP, for a time horizon of one hundred years) corresponding to the alloy design which is being studied. This parameter, expressed in [kg CO_2e/ton steel], quantifies the carbon footprint of a steel product and it is becoming increasingly important for customers to keep it to a minimum.

These tools will be detailed below.

2. ALLOY DESIGN OPTIMIZATION - ADO

Alloy Design Optimizer (a.k.a. ADO) is an Excel application developed by CBMM that allows the comparison between real and proposed alloy designs of Nb microalloyed steels. It was developed to optimize chemical composition, as well as the corresponding process parameters, in order to minimize alloy costs while keeping or even upgrading product performance. ADO has an internal mathematical model for the prediction of mechanical properties of microalloyed steels. To obtain the best results, this mathematical model must be developed for each hot flat rolling line under analysis. ADO has an internal mathematical model for the prediction of mechanical properties of microalloyed steels.

The main components of ADO are:

- *Calculator*: this is the main spreadsheet, where data about steel chemical composition and rolling process is input; results are output here as well.
- *User Notes*: brief information about ADO functions.
- *Model Limits*: show the validity ranges of the alloy contents and hot rolling process parameters which are specific for the specific model included at an ADO version.
- *References*: public literature used in the development of ADO.
- *Alloy Cost Simulator*: updated info about ferroalloys (price, recovery, and so on) must be input here.

The mathematical model used by ADO to calculate product mechanical properties from steel chemical composition and hot rolling parameters data is interchangeable and programmed in Visual Basic Application language. ADO can use any model of this kind available in the public literature, like the equations below, developed by British Steel [2]:

$$UYS = 73 + 166\sqrt{C} + 40Si + 38Mn + 1547Nb + 357\sqrt{V} + 12.35d^{-1/2} + UYS_{FRT} + UYS_P \quad (1)$$

where:

$$UYS_{FRT} = 0.446\Delta T_{FRT}$$
$$UYS_P = 254\sqrt{V} - 9395Ti$$
$$\Delta T_{FRT} = Ae_3 - FRT + 100$$

$$UTS = 84 + 627\sqrt{C} + 71Si + 76Mn + 1004Nb + 320\sqrt{V} + 4.40d^{-1/2} + UTS_{FRT} + UTS_P \quad (2)$$

where:

$$UTS_{FRT} = 0.256\Delta T_{FRT}$$
$$UTS_P = 318\sqrt{V} - 10676Ti$$

However, to achieve maximum precision and relevance, it is strongly recommended that, before using ADO to analyze the performance of the products of a given rolling line, a specific mathematical model is developed to calculate mechanical properties for that specific line and type of products considered. This is usually done through statistical analysis of huge and detailed data sets including chemical composition, process parameters and the corresponding mechanical properties from the same line being analyzed [3].

ADO requires the following data:

- Thickness of slab and final flat product;
- Chemical composition of steel;
- Hot rolling process parameters (in function of the specific model that is being used);
- Updated characteristics and costs of ferroalloys.

Then ADO can generate the following information:

- Relevant metallurgical process parameters (in function of the specific model that is being used);
- Mechanical properties of the flat product (generally yield and tensile strength);
- Alloy costs, according to the alloy design being studied;
- Process costs (optional, only if given by the steel producer).

The color of the spreadsheet cells indicates data priority or kind, in function of the specific model that is being used:

- Green: mandatory input data;
- Blue: optional input data;
- Yellow: output of results calculated by ADO.

The Calculator component of the ADO has the following sections:

- *Material*: identification and geometric data of slab and final flat product (Figure 1).

MATERIAL			
Grade	Slab Thickness [mm]	Slab Weight [t]	Final Plate Thickness [mm]
1	238	6.0	15.50
2	238	6.0	15.50
3	250	6.0	18.00
4	250	6.0	18.00
5	250	6.0	22.00
6	250	6.0	22.00

Figure 1: Material section data of ADO.

- *Alloy Design*: Input of chemical composition of the studied steels. One can note in Figure 2 that some numbers are in red color. This is a warning, because ADO has already run and identified that these values extrapolated the valid range of the current model, according to data in the Model Limits spreadsheet.

LEAN ALLOY DESIGN																
C [%]	Si [%]	Mn [%]	P [%]	S [%]	Al [%]	Nb [%]	Ti [%]	V [%]	Cu [%]	Ni [%]	Cr [%]	Mo [%]	W [%]	N [%]	B [%]	Sn [%]
0.137	0.38	1.44	0.010	0.001	0.040	0.001	0.003	0.002	0.02	0.01	0.03	0.01	0.00	0.0036	0.0001	0.0005
0.137	0.38	1.00	0.010	0.001	0.040	0.010	0.003	0.002	0.02	0.01	0.03	0.01	0.00	0.0036	0.0001	0.0005
0.124	0.40	1.56	0.010	0.001	0.046	0.001	0.003	0.002	0.02	0.01	0.03	0.01	0.00	0.0036	0.0001	0.0005
0.124	0.40	1.00	0.010	0.001	0.046	0.010	0.003	0.002	0.02	0.01	0.03	0.01	0.00	0.0036	0.0001	0.0005
0.165	0.40	1.48	0.010	0.001	0.044	0.017	0.002	0.002	0.02	0.01	0.03	0.01	0.00	0.0044	0.0001	0.0005
0.165	0.40	1.88	0.010	0.001	0.044	0.012	0.002	0.002	0.02	0.01	0.03	0.01	0.00	0.0044	0.0001	0.0005

Figure 2: Alloy Design section.

- *Weldability and Peritectic Range*: Output of quality parameters calculated by ADO using chemical composition data input by user, as shown in Figure 3: *Weldability*, expressed by carbon equivalent formulas (CE_q and P_{cm} [4]), *Hot Ductility* (Mn/S ratio and minimum Mn amount that must be present in steel to avoid plate cracking during hot rolling [5]) and *Peritectic Criticality* (expressed by the mold temperature standard deviation, that must be as low as possible in order to minimize slab cracking due to peritectic transformation during continuous casting [6]).

WELDABILITY AND PERITECTIC RANGE					
C_{eq}	P_{cm}	Mn/S	Mn_{Min} [%]	C_{eq} Peritectic	Mold Temp Standard Deviation [°C]
0.39	0.23	1440	0.32	0.18	2.87
0.31	0.20	1000	0.32	0.16	2.81
0.39	0.22	1556	0.32	0.19	2.80
0.30	0.19	1000	0.32	0.15	2.82
0.42	0.26	1475	0.32	0.22	1.16
0.49	0.28	1880	0.32	0.30	1.16

Figure 3: Weldability and Peritectic Range section.

- *Furnace Temperatures*: As seen in Figure 4, *Reheat Temperature* must be input by user if required by the mechanical properties model; *Solution Temperature*, calculated by ADO is the minimum temperature to achieve full niobium dissolution defined by the Irvine equation [7].

FURNACE TEMPERATURES	
Reheat Temperature [°C]	Solution Temperature (Irvine) [°C]
1138	-
1138	1048
1152	-
1152	1037
1152	1134
1152	1091

Figure 4: Furnace Temperatures section.

- *Rolling Process Temperatures*: Certain temperatures of the rolling process need to be provided by the user as required by the model for predicting mechanical properties, as described in Figure 5. In addition, ADO calculates some critical temperatures using the chemical composition of steel, like the boundaries of austenite recrystallization kinetics (Recrystallization Limit Temperature and Recrystallization Stop Temperature [8]) and the start of the austenite transformation in ferrite (A_{r3}, [9]).

ROLLING PROCESS TEMPERATURES								
Start Roughing Temperature [°C]	Finish Roughing Temperature [°C]	RLT (Bai 2011) [°C]	Holding Thickness [mm]	Holding Time [s]	Start Finishing Temperature [°C]	RST (Bai 2011) [°C]	Finish Rolling Temperature [°C]	Ar3 (Ouchi) [°C]
		-				-	906	750
		946				871	906	785
		-				-	946	745
		938				863	946	789
		1000				925		739
		974				899		706

Figure 5: Rolling Process Temperatures section.

- *Cooling Temperatures*: eventually cooling start/end temperatures and cooling rate of the rolling process must also be provided by the user as required by the specific model for predicting mechanical properties, as described in Figure 6.

- *Comparable Properties with Reduced Costs*: this section shows the results of the mechanical properties model (Figure 7). Optionally the user can input real measured results of yield/tensile strength and elongation (blue legend) only for comparative purposes with the corresponding calculated results (yellow legend). ADO also calculates the associated ferroalloy costs for Mn, Nb, V and Si, total costs and the difference between two subsequent alloy designs.

COOLING TEMPERATURES		
Start Cooling Temperature [°C]	Cooling Rate [°C/s]	Finish Cooling Temperature [°C]

Figure 6: Cooling Temperatures section.

COMPARABLE PROPERTIES WITH REDUCED COSTS											
YS [MPa]	TS [MPa]	Elong [%]	YS_{calc} [MPa]	TS_{calc} [MPa]	$Elong_{calc}$ [%]	Cost Mn [US$/t]	Cost Nb [US$/t]	Cost V [US$/t]	Cost Si [US$/t]	Alloy Total Cost [US$/t]	Delta Cost Alloy [US$/t]
412	547	26	402	545		22.59	0.36	0.65	7.97	35.24	
			406	529		15.69	3.61	0.65	8.06	31.68	3.57
374	526	23	406	551		24.41	0.36	0.65	8.57	37.66	
			406	529		15.69	3.61	0.65	8.57	32.18	5.47
			Nb High!	Nb High!		23.14	6.14	0.65	8.57	42.16	
			442	579		29.49	4.33	0.65	8.57	46.71	-4.55

Figure 7: Comparable Properties with Reduced Costs section.

3. ECO NB

Recent developments proved that it is possible to reduce manganese content by adding small amounts of niobium, keeping the same mechanical properties of structural steels plates. For low yield strength around 350 MPa, small additions of niobium like 0.010% are enough to maintain the same mechanical properties of the material even reducing 0.50% of manganese content [10]. Figures 1 to 7 show several examples of the economical advantage of such approach.

However, there are additional profits from this new alloy design when steel refining processes are considered. The reduction of manganese content results in less additions of FeMn, allowing to decrease the tapping temperature. This brings many benefits, e.g., regarding the consumption of refractories of BOF furnace and ladle, the increase of metallic yield, savings of electrical energy and electrodes at the ladle furnace, the reduction of amount of aluminum as deoxidizer, of absorbed hydrogen and nitrogen, and of macro segregation. EcoNb is a digital tool developed to quantify such benefits. Figure 8 shows the results of a EcoNb calculation showing the benefits got from the partial substitution of Mn by Nb in a specific structural steel, that is, from a steel with 1.40% Mn and no Nb to another one with 0.90% Mn and 0.010% Nb.

These benefits are indirect for the customer, but one is becoming very important, that is, the calculation of the Global Warming Potential (GWP, for a time horizon of one hundred years) referring to the chemical compositions of conventional steel and new alloys proposed, with lower Mn content compensated by a micro addition of Nb. Although this calculation still is controversial, as the values of GWP obtained depend on a myriad of factors, including the manufacturing route of each plant and its energy sources, it is a good indication of the minimization of the carbon footprint of the steel. As shown in Figure 8, the results obtained in terms of the Global Warming Potential for produce structural steels were favorable for the new Low Mn-Nb steel, with an average reduction of 62 kg of CO_2 equivalents per ton of product, a not negligible bonus considering the pressure being put on the steel industry to reduce its carbon footprint. Considering that a typical passenger car emits about 4.6 tons of CO_2 per year (or 12,6 kg of CO_2 a day), the reduction in the CO_2 footprint due to the partial replacement of Mn by Nb showed in Figure 8 compensates 4.9 days of a car use for each rolled ton of steel [13].

4. CONCLUSIONS

It was shown in this work how two digital tools developed by CBMM – *Alloy Design Optimization (ADO)* and *ecoNb* – are helping to accelerate and make the process of developing structural steel alloys projects more accurate. In this specific opportunity, these tools are supporting the effort of creating more refined products with lower cost and carbon footprint through the partial exchange of manganese for micro additions of niobium. These applications are continuously being improved in order to cover, with greater precision, a wider range of structural products.

ECONOMY				
Slag Splashing (0)	Gunning (1)	1		
Energy Savings: Tapping Temperature (°C)		16		
Addition Savings: FeSiMn (Kg/t LOW Mn)		8.651	US$/t	12.11
Addition Savings: Al Deoxidation (Kg/t LOW Mn)		0.141	US$/t	0.39
SAVING BOF LINING REFRACTORY (Kg/t LOW Mn)	GUNNING	0.116	US$/t	0.23
	SLAG SPLASHING		US$/t	
SAVING STEEL LADLE LINING REFRACTORY (Kg/t LOW Mn)		0.050	US$/t	0.04
INCREASE METALLIC YIELD (%)		0.66	US$/t	0.81
Ladle Furnace Savings (ONLY IF TAPPING TEMPERATURE: ALLOWED < NEEDED)	Electrical Energy (KWH/t LOW Mn)	123	US$/t	0.03
	Electrode (Kg/t LOW Mn)	0.100	US$/t	0.19
TOTAL SAVING		US$/t LOW Mn		13.80
DECREASE "P" CONTENT at TAPPING		ppm		34.5
DECREASE "H" CONTENT in STEEL LADLE		ppm		1.7
DECREASE "N" CONTENT in STEEL LADLE		ppm		6.7
DECREASE "S" CONTENT in STEEL LADLE		ppm		2.0
Reduction of Manganese Centerline Segregation		%		67
Saving in Global Warming Potential (GWP)		Kg CO_{2e} / tonne		62

Figure 8: Alloy design change evaluation report generated by ecoNb: from a steel with 1.40% Mn and no Nb to another one with 0.90% Mn and 0.010% Nb [1].

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