DEVELOPMENT OF 510 MPA STRENGTH CLASS STEEL PLATES WITH HIGH TOUGHNESS PRODUCED BY ACCELERATED COOLING IN GERDAU OURO BRANCO*

Romeu Thomaz Viana Jr[1]
Afonso Cardoso da Silva[2]
Emanuelle Garcia Reis[3]
José Herbert Dolabela da Silveira[4]
Mateus Pedro Medeiros da Silva[5]
Rafael Abreu Fraga[6]
Ricardo José de Faria[7]

Abstract
The Gerdau Ouro Branco Mill, three years after the implementation of its new plate mill, has started to develop high complexity products. The plate mill's learning curve has been increasingly challenging since products are being developed to their highest grades. This work aims to present the first results of the development of steels of the strength class of 510 MPa produced by TMCP (Thermomechanical Controlled Processing) followed by accelerated cooling. These results show the potential and advantage of the accelerated cooling process regarding to obtain products of high mechanical strength and high toughness, associated with a low equivalent carbon.
Keywords: Plate Mill; Controlled rolling; Accelerated cooling; Toughness.

[1] *Metallurgical Engineer, Plate Mill Specialist, Plate Mill Department, Gerdau, Ouro Branco, MG, Brazil.*
[2] *Metallurgy Technician, Laboratory Technician, Laboratory Department, Gerdau, Ouro Branco, MG, Brazil.*
[3] *Civill Engineer, M. Eng., Plate Mill Senior Specialist, Plate Mill Department, Gerdau, Ouro Branco, MG, Brazil.*
[4] *Metallurgical Engineer, M. Eng., Plate Mill Technical Manager, Plate Mill Department, Gerdau, Ouro Branco, MG, Brazil.*
[5] *Mechanical Technician, Laboratory Technician, Laboratory Department, Gerdau, Ouro Branco, MG, Brazil.*
[6] *Metallurgical Engineer, Plate Mill Senior Specialist, Plate Mill Department, Gerdau, Ouro Branco, MG, Brazil.*
[7] *Metallurgical Engineer, M. Eng., Products and Process Senior Specialist, R&D Department, Gerdau, Ouro Branco, MG, Brazil.*

1 INTRODUCTION

The controlled rolling of thick plates made from micro-alloyed steels is a thermomechanical treatment established several decades ago, but its technical evolution is continuous, as there is an increasing need to produce sophisticated products at ever smaller costs to cope with the strong competition that exists in the global steel industry.
Figures 1 shows the relationship between market requirements and the role of thermomechanical treatment [1]. Since the first application of this process in the naval industry, its products have been applied in many plate markets, as shown in table 1 [1]. Its popularity reflects the advantages of micro-alloyed steels processed by controlled rolling, such as better mechanical strength and toughness, associated with excellent weldability. Another key factor that reflects the advantages of this thermomechanical treatment is the fact that alloy design, control of impurities during the steelmaking process, reduction of segregation, removal of hydrogen, reheating of plates and the processes of rolling and cooling are considered both in previous and post-rolling processes.

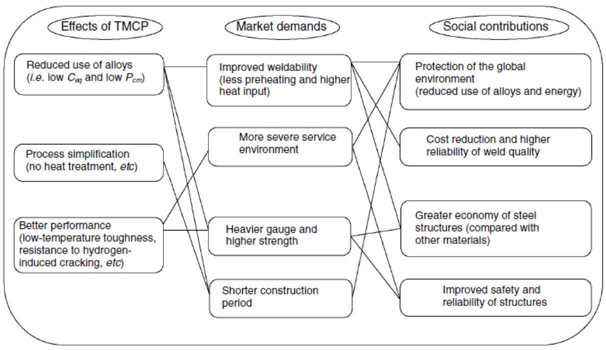

Figure 1. Relationship between market requirements and the roles of thermomechanical treatment [1].

Table 1. Tensile strength classes and applications of thick plates processed through TMCP [1]

Application	Tensile Strength Class [MPa]				
	490	590	690	780	900-950
Naval	○	○	-	-	-
Offshore Structures	○	○	-	●	-
Large Diameter Tubes	○	○	○	○	○
Construction	○	○	-	○	-
Bridges	○	○	-	○	-
Gates	○	●	●	●	●
Low Temperature Tanks	○	○	-	-	-
Cryogenic Tanks	○	-	○	-	-
Earthmoving Equipment	○	○	●	●	●

○ Accelerated Cooling (and Tempered)
● Direct Quenching and Tempered

The advent of controlled rolling allowed to reduce the equivalent carbon of structural thick plates without affecting its mechanical characteristics, since the effects of the alloying elements were replaced by an intense grain size refining. In fact, this feature allows to increase both yield strength and toughness, but does not increase the resistance limit so much, which limits the possibilities of adopting lighter chemical compositions [2-4].
The next step in this evolution was the accelerated cooling of thick plates after rolling through the application of water. This metallurgical resource was only feasible after solving several complex technical problems. This only occurred in the early 1980s, thanks to the efforts of several mills,
mainly Japanese [5]:
- Ensure good flatness in the plate to avoid irregular accumulations of water;
- Surface of the rolled product totally free from coarse scale to maintain uniform cooling;
- Adequate level of line automation to ensure accuracy and uniformity at the

temperature of the plate before accelerated cooling;
- Development of water application control systems that consistent and uniform cooling rates throughout the plate.

Today the use of water as an alloying element is a well-established technology, as demonstrated by the spread of accelerated cooling lines around the world. This process allows the most adequate microstructures to be obtained according to the required mechanical characteristics, as well as to reduce the contents of the alloying elements and to make the controlled rolling process less rigid, contributing to increase the productivity of the thick plates.

The accelerated cooling allows the reduction of alloying elements directly impacting the production cost of the steel, thus it is possible to obtain steels with more refined and more homogeneous microstructures than the steels obtained through conventional rolling without accelerated cooling besides a range of mechanical properties and microconstituents depending on the cooling condition.

For accelerated cooling to be effective thermomechanical rolling is required to obtain a larger fraction of elongated and refined grains, which will later serve as nucleation points of ferritic grains. After this procedure, the application of the accelerated cooling allows to control the transformation of phases, to obtain the desired microstructure [1].

The new Gerdau Plate Mill has the so-called "State of the Art" in its equipment and process technology. A close design of 900 meters in length with a capacity of 1.2 million t / year of thick plates in thicknesses between 6.0 and 150 mm and widths between 900 and 3,700 mm. The rolling line is comprised of a plate reheating furnace, a thick plate mill, pre-leveler machine, an accelerated cooling system (Mulpic) and hot leveler. Such equipment is used to obtain high strength and low alloy steels with high toughness requirements.

2 MATERIAL AND METHODS

The alloy design adopted in this study was a C-Mn steel micro alloyed to Nb and Ti plus Cu and Ni. The route in the steelworks of this steel included treatment in ladle furnace, degassing RH and injection of Ca for globulization of inclusions.

The slabs were reheated under enough temperature to solubilize the Nb according to the value predicted by the Irvine equation [6], but discounted in N content as a function of its stoichiometric reaction with Ti. The rolling was carried out with a waiting period between the roughing and finishing phases. After the wait phase, the finishing was started under temperatures below the non-recrystallization temperature, according to the value calculated by Boratto [7], with the final rolling occurring with the fully austenitic plate, that is, at temperatures above Ar3, as calculated by Ouchi [8].

The accelerated cooling started shortly after the outflow of the plate from the mill, in temperatures above Bs. Therefore, the temperature at the end of the accelerated cooling was just below Bf, as calculated by Steven & Haynes [9].

The slabs were hot rolled in plates with thicknesses of 25.40 and 50.80 mm, and the values proposed for the specification of mechanical properties for the plates of this study were: minimum yield strength of 400 MPa; resistance limit between 510 and 650 MPa; and minimum total elongation, with a measurement basis of 5.65 $\sqrt{A0}$ equal to 20%. The results of Charpy impact resistance were determined under temperatures of -20°C, -40°C and -60°C, requiring a minimum energy value of 40J.

Describe succinctly the equipment and procedures used, as the literature and the statistical methods and the corresponding literature, as the case demands.

The tension tests were carried out using test specimens machined in the cross direction of rolling of the plates. In turn, the Charpy impact tests were performed using

10 mm x 10 mm specimens, machined in the longitudinal direction of rolling of the plates and using "V" shaped notches.

3 RESULTS AND DISCUSSION

Tables 2 and 3 show the results obtained in the tension tests of the plates analyzed in this study. As can be seen, the proposed mechanical properties requirements were fully met. It is noteworthy that the maximum difference in mechanical properties between the top and bottom of the plates was 31 MPa for plates with a thickness of 25.40 mm, which demonstrates the good operational stability of the accelerated cooling process, as can be observed in thermographs present in Figures 2 and 3.

Table 2. Tension tests results of the plates with 25.40 mm thickness.

Plate	Thickness (mm)	Tension Test (Transversal Specimen)					
		YS Avg. (MPa)	TS Avg. (MPa)	YS/TS Avg.	EL 5.65 $\sqrt{A_0}$ Avg. (%)	Δ YS T and B (MPa)	Δ TS T and B (MPa)
1	25.40	455	556	0.82	27	29	28
2		472	566	0.83	27	28	27
3		480	570	0.84	27	2	13
4		470	563	0.82	29	31	27

Table 3. Tension tests results of the plates with 50.80 mm thickness.

Plate	Thickness (mm)	Tension Test (Transversal Specimen)					
		YS Avg. (MPa)	TS Avg. (MPa)	YS/TS Avg.	EL 5.65 $\sqrt{A_0}$ Avg. (%)	Δ YS T and B (MPa)	Δ TS T and B (MPa)
1	50.80	443	546	0.81	26	13	14
2		445	555	0.80	26	0	6
3		439	553	0.79	26	4	10
4		449	557	0.80	25	16	0

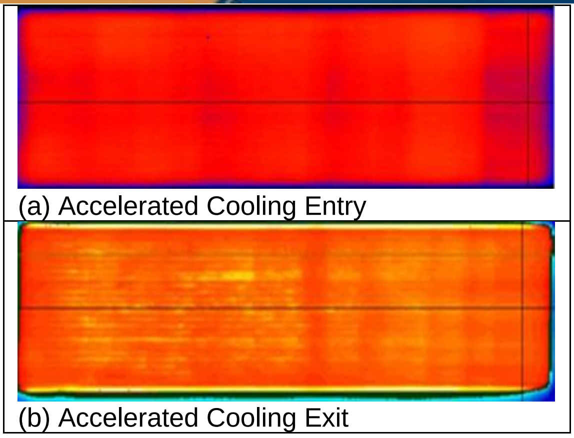

Figure 2. Photographs of entry (a) and exit (b) of the accelerated cooling process of the plate with 25.40 mm thickness.

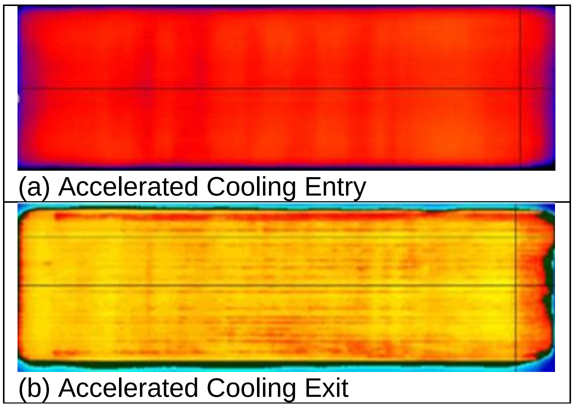

Figure 3. Photographs of entry (a) and exit (b) of the accelerated cooling process of the plate with 50.80 mm thickness.

Figure 4 shows the photos of some 25,40 mm thick plates in the cooling bed, where we can observe good flatness materials.

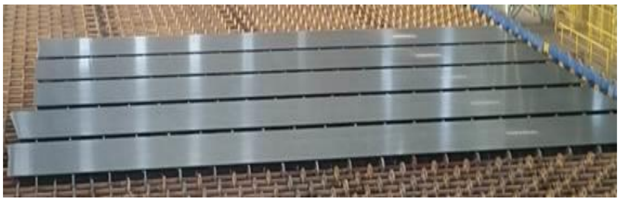

Figure 4: Plates of 25.40 mm in the cooling bed.

Tables 4 and 5 show the results obtained in the Charpy impact test of the samples extracted from the plates used in this study. As can be seen, the requirements of established mechanical properties have been fully met. It is noteworthy that, even in tests conducted under the minimum temperature of -60°C, the results of absorbed energy remained above 90J.

Table 4. Charpy impact tests results of the plates with 25.40 mm thickness.

Plate	Thickness (mm)	Average Energy Absorbed (J)		
		- 20°C	- 40°C	- 60°C
1	25.40	418	409	220
2		418	378	234
3		431	434	169
4		411	418	118

Table 5. Charpy impact tests results of the plates with 50.80 mm thickness.

Plate	Thickness (mm)	Average Energy Absorbed (J)		
		- 20°C	- 40°C	- 60°C
1	50.80	412	391	98
2		315	269	132
3		415	409	121
4		416	409	116

Figures 5 and 6 show two microstructures of different samples from thick plates of 25.40 and 50.80 mm thickness, respectively, seen under different magnifications. The microstructures presented a mixed character with well refined acicular constituents, similar to what is expected for micro alloyed steels subjected to the thermomechanical treatment described here, as well as polygonal ferrite grains.

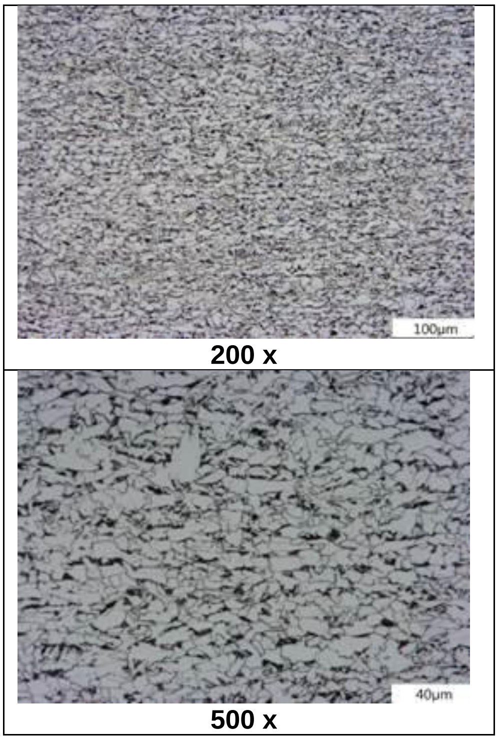

Figure 5. Typical microstructures at ¼ of the thickness of 25.40 mm plates. Nital etching 3%.

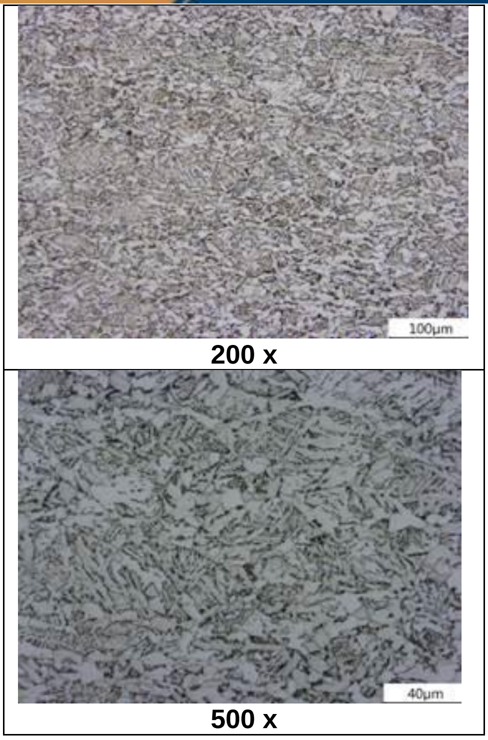

Figure 6. Typical microstructures at ¼ of the thickness of 50.80 mm plates. Nital etching 3%.

4 CONCLUSION

Information related to mechanical strength, toughness, microstructure and thermomechanical rolling followed by accelerated cooling were presented in this work.

The mechanical properties results were compatible with those expected for a NbTi micro alloyed C-Mn steel, processed through controlled rolling and accelerated cooling.

The differences in mechanical strength between top and bottom as well as the flatness of the materials have demonstrated the good stability of the accelerated cooling process, which is of utmost importance for the microstructure consistency and mechanical properties of the final product.

REFERENCES

1 Nishioka K, Ichikawa K. Progress in Thermomechanical Control of Steel Plates and their Commercialization. Science and Technology of Advanced Materials. 2012;13; p.1-20.

2 NISHIOKA, K. Steel World, 5:1, 2000, 61-67.

3 STREIβELBERGER, A., SCHWINN, V. & HUBO, R. In: Niobium 2001 – Science & Technology. Proceedings. The Metals Society-Companhia Brasileira de Metalurgia e Mineração, 2001, 625-646.

4 EVANS, J.F. & CLARK, M.T. AISE Steel Technology, June 2002, 49-53.

5 KIRSCH, H.J., FLÜβ, P., SCHÜTZ, W. & STREIβELBERGER, A. Stahl und Eisen, 119:3, März 1999, 57-65.

6 Irvine KJ, Pickering FB, Gladman T. Grain-Refined C-Mn Steels. Journal of the Iron and Steel Institute, 1967, 205:161-182.

7 Boratto F, Barbosa R, Yue S, Jonas JJ. The Influence of Chemical Composition on the Recrystallisation Behaviour of Microalloyed Steels. In: Processing, Microstructure and Properties of HSLA Steels. Proceedings… The Metallurgical Society of AIME, Pittsburgh, 1987, p. 51-61.

8 Ouchi C, Sampey T, Kosazu I. The Effect of Hot Rolling Condition and Chemical Composition on the Onset Temperature of Gamma-Alpha Transformation After Hot Rolling. Transactions of the ISIJ. 1982;22(3):214-222.

9 Steven W, Haynes AG The Temperature of Formation of Martensite and Bainite in Low Alloy Steels. Journal of the Iron and Steel Institute. 1956;183:349-359.