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Study of the Mechanical Properties and Fracture Morphology Of Niobium Microalloyed 80 ksi Class Thick Plates Produced by Controlled Rolling Followed by Accelerated Cooling

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Abstract

This paper describes the first production trials of 80 ksi class thermomechanically controlled processing (TMCP) thick plates at the new Gerdau Ouro Branco plate mill. These trials were very successful, as the product fully satisfied the mechanical properties requirements for such grade, enabling the start of commercial delivery of this material. In addition, experience gained in this process will promote further technological improvement of this class of products, as well more sophisticated plates. The occurrence of separations in the fractured surface of Charpy specimens was considered with detail.

Introduction

The thermomechanically controlled processing (TMCP) thick plates made with microalloyed steels was several decades ago, but its technical evolution is continuous, as there is an increasing need to produce sophisticated products at ever smaller costs in order to face the strong competition that exists in the global steel industry.

Figure 1 shows the relationship between market requirements and the role of thermomechanical treatment (Nishioka 2012). Since the first application of this process in the shipbuilding industry, its products have been applied in many plate markets, as shown in **Table 1** (Nishioka 2012). Its popularity reflects the advantages of microalloyed 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, impurities control 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.

Gerdau, which started last year the activities of its new plate mill at the Ouro Branco steelworks, Brazil, launched an ambitious program to develop thermomechanical treatments for micro-alloyed steels that take full advantage of all the latest technological features of its equipment, including the Mulpic line for accelerated cooling and direct quenching. The ultimate goal is the consistent production of high value-added products that fully meet the demands of its customers. Among these products are thick plates with a grade of 80 ksi (i.e. with a minimum yield strength of 80 ksi or 555 MPa), which are the subject of the present work.

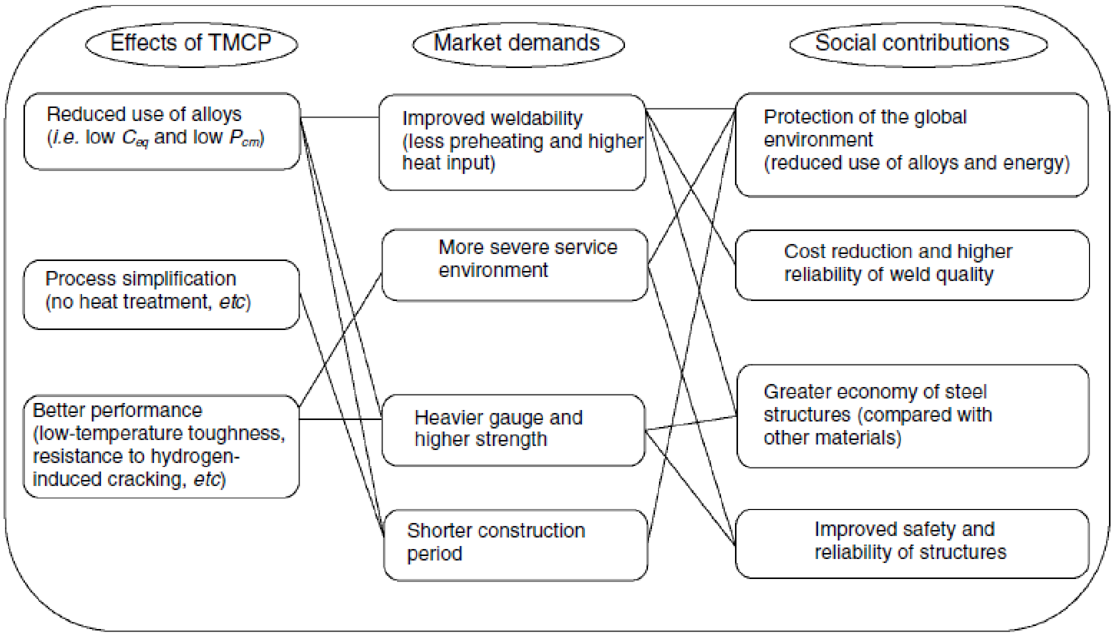


Fig. 1 - Relationship between market requirements and the roles of thermomechanical treatment (Nishioka 2012).

Application	Tensile Strength Class [MPa]				
	490	590	690	780	900-950
Shipbuilding	○	○	-	-	-
Offshore Structures	○	○	-	●	-
Line Pipes	○	○	○	○	○
Buildings	○	○	-	○	-
Bridges	○	○	-	○	-
Penstocks	○	●	●	●	●
Low-Temperature Storage Tanks	○	○	-	-	-
Cryogenic Storage Tanks	○	-	○	-	-
Earthmoving Equipment	○	○	●	●	●

○ Accelerated Cooling (and tempering)
● Direct Quenching and Tempering

Table 1 - Tensile strength classes and applications of thick plates processed through TMCP (Nishioka 2012).

This product class represents a transition point in microstructural terms. Steel plates with a yield strength up to 70 ksi (485 MPa) generally have a ferrite-pearlite microstructure. The modern 80 ksi class plates have a ferrite-bainite or acicular ferrite microstructure (DeArdo 2016). The initial versions of these thick plates, produced in lines without accelerated cooling, were already based on hardening mechanisms that tried, as much as possible, to minimize the carbon content of the steel to guarantee its toughness and weldability: refined ferrite with MA constituent (API 5L X80) (Lazzari 1988), Cu precipitation hardening (HSLA-80) and bainite with extra-low C content (ULCB) (Gorni 2005). The implementation of accelerated cooling allowed the production of 80 ksi grade material using even leaner chemical compositions and with a higher consistency of mechanical properties (Nishioka 2012).

An ocorrence well known in the thermomechanical controlled processing of HSLA steels is the appearance of so-called "separations" on the fracture surface of the specimens submitted to the Charpy test. These are cracks that propagate through the transverse plane in relation to the main plane of the fracture. Its effect on the quality of the material is controversial. There are those who affirm that their formation is favorable, since it reduces the ductile-brittle transition temperature and improves the energy value of the upper plateau in some directions, acting as a crack interceptor. However, in general, the appearance of the separations is considered undesirable since they reduce the impact-absorbing capacity of the Charpy specimens machined along the transverse-longitudinal orientation (TL) with respect to the rolled plates (Ghosh 2016).

The identification of the cause of the "separations" has been promoting a debate since the 1970s, when the TMCP steels became relatively common. It has been proposed that they are formed from particles of inclusions/carbides in the grain boundaries, the elongated structure of ferritic grains, regions with unfavorable crystallographic texture and banded microstructures (Ghosh 2016). However, in the new steels with a high degree of inclusionary cleanness, the emergence of separations is not associated with non-metallic inclusions. It has been observed, especially in the case of 80 ksi steels produced by several steelworks, that this occurrence originates from the layered structure produced during the finishing phase of the controlled rolling, particularly in the intercritical region, where austenite and ferrite coexist, that is, when the rolling stock is finished under the A_{r3} and A_{r1} temperatures (Farber 2016). The separation crack has a ductile propagation along the crystallographic texture bands formed during intercritical rolling due to strain incompability (Ghosh 2017).

Experimental Procedure

The alloy design adopted at this time for the manufacture of 25 mm thick plates with a minimum yield strength of 80 ksi (555 MPa) was a microalloyed MnNbTiVCrMo steel with low C, one of the established approaches for this type of product (Gorni 2010). The elaboration route at the steelworks for this steel included treatment in ladle furnace, RH degassing and Ca injection for the globulization of inclusions.

According to the practice already established for the thermomechanical controlled processing of microalloy steels, the slabs were reheated at a temperature enough to fully dissolve Nb, according to the value predicted by the equation proposed by Irvine (1967), but with a decrease of N content as a function of its reaction under stoichiometric ratio with Ti. The pass schedule during the roughing phase was carried out in order to apply increasing reductions per pass after the broadsizing phase. It has already been proven that this pass schedule strategy contributes to both greater refining and uniformity of grain size, promoting improved toughness results, since heavier strains are applied in a relatively lighter rolling stock, facilitating strain penetration to its core. After the holding phase, finishing rolling was started at temperatures below the non-recrystallization temperature (T_{nr}), as calculated by Boratto (1987), with finishing rolling occurring as much as possible with a fully austenitic rolling stock, that is, at temperatures above A_{r3}, as calculated by Ouchi (1982). The finishing rolling in the austenitic field offers a number of advantages, such as a faster thermomechanical treatment, suppression of the loss of toughness due to the presence of strain hardened ferrite and the reduction of the probability of the appearance of the controversial so-called separations in the fracture surface of the fractured specimens after toughness tests.

The accelerated cooling started as soon as possible, at temperatures above B_s, as calculated by Steven & Haynes (1956). The final temperature of the accelerated cooling varied according to the rolling stock length, from slightly above to below B_f, calculated by the same authors. This temperature profile was adopted to check the possibility of the formation of a greater amount of constituent MA in the microstructure and the consequent degradation in the toughness that tends to occur if accelerated cooling ends at a too low temperature (Huda 2016).

After rolling, tensile tests were performed using specimens machined in the transversal direction of the rolling stock, whose gage length L_0 was equal to 88 mm. Vickers hardness was also measured under a 10 kg load. Charpy impact tests were carried out using specimens measuring 10 mm x 10 mm, machined in the longitudinal direction at ¼ thickness of the rolling stock and using V-shaped notch. Charpy tests were performed at temperatures of -20, -40 and -60°C.

The intensity of the formation of the separations present on the fractured surface of the Charpy test specimens needed to be quantitatively characterized to allow the establishment of correlations with the process variables and test conditions. Farber (2016) proposed a laborious method involving the measurement of the areas affected by separations on the fractured surface of the Charpy test specimen. However, a simpler approach, proposed by Fernandes (2010), requires only the measurement of the lengths of the separations, as their length:width ratio was roughy constant. It was adopted here, as it was considered more convenient for the purposes of this work. These measurements were performed using an stereoscopic magnifier attached to a video camera. The image of the fracture was shown in a display and the length measurements of the separations were done manually.

It was aimed that these plates, with thickness of 25 mm, should meet the following mechanical properties specifications: yield strength between 542 and 662 MPa; tensile strength between 631 and 741 MPa;

minimum elongation of 23% and maximum yield ratio of 0.93. The results of Charpy toughness were determined under temperatures of -20, -40 and -60°C, but no minimum values were specified within this work.

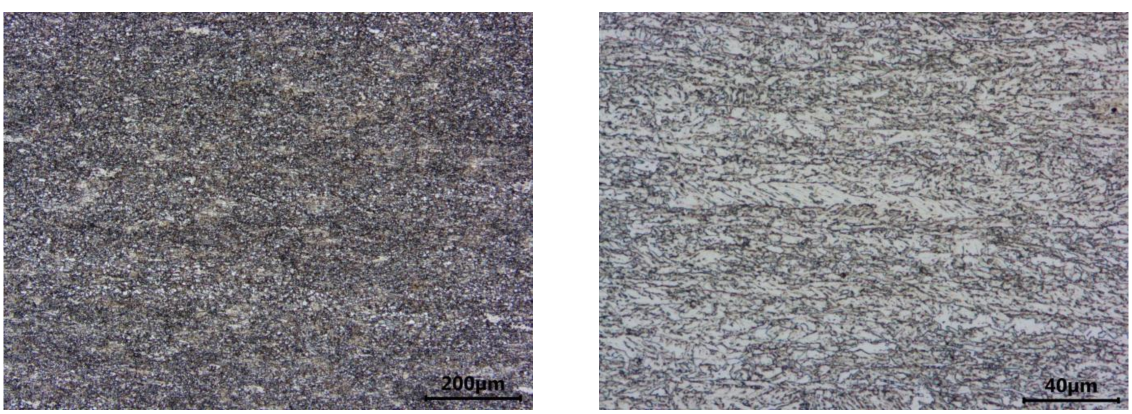
Results and Discussion

Table 2 shows the results obtained in the 80 ksi thick plates processed by TMCP of the MnNbTiVCrMo microalloyed steel at the best value of final accelerated cooling temperature. As can be seen, the mechanical properties requirements were fully met, including the results of 180° transversal bending tests, which are not shown in that table. No correlation of the various mechanical properties with the applied process parameters was observed, which indicates relative stability to normal variations in operating conditions, except regarding the occurrence of separations, as discussed below.

Figure 2 shows the microstructures at ¼ thickness of a 80 ksi thick plate made with the MnNbTiVCrMo microalloyed steel, seen under different magnifications. The microstructures presented acicular character, very similar to what is expected for the bainite of steels with very low carbon content submitted to the thermomechanical treatment described here, besides sparse grains of polygonal or quasi-polygonal ferrite. According to Meimeth et al. (2006), this microstructure with predominance of bainite and ferrite traces is typical of 80 ksi grade steels, which requires the presence of at least 85% bainite in the microstructure to achieve this level of mechanical strength. It is also possible to observe in this figure the total absence of microstructural banding.

Tensile Test (Transversal Specimen)				Charpy Average Energy (Longitudinal Specimen, ¼ Thickness)			Average Hardness 1.5 mm depth	
$YS_{0,5\%}$ [MPa]	YS [MPa]	YS/TS	EL [%]	-20°C [J]	-40°C [J]	-60°C [J]	Face A [HV10]	Face B [HV10]
591	686	0.86	43	430	367	362	223	231
611	697	0.88	44	400	335	358	224	233
574	677	0.85	42	463	448	401	223	229
597	694	0.86	43	437	406	391	223	231
571	687	0.83	44	411	346	338	237	246

Table 2 - Mechanical properties obtained in thick plates of MnNbTiVCrMo microalloyed steel after thermomechanical treatment satisfying the 80 ksi grade specifications.



(a) 100 x (b) 500 x

Fig. 2 - Microstructures at ¼ thickness of the 80 ksi grade plates of MnNbTiVCrMo microalloyed steel. Nital 3% etch.

Despite the high values of absorbed energy revealed by Charpy impact tests, as shown in Table 2, several occurrences of separations were observed on the fracture surfaces of the broken specimens after this test, as can be seen in the example shown in **Figure 3**. Surprisingly, separations also appeared in the fractured surface of Charpy specimens that where extracted from rolling stocks whose finishing temperatures were nominally higher than A_{r3}, albeit with lower intensity. This can be explained by the fact that this parameter actually represents an average value of all the finishing temperature values determined across the entire width, thickness and length of the rolling stock. However, unavoidable temperature gradients exist in the just as-rolled plate, mainly through its thickness. So, the surface of the rolling stock will always show a temperature lower than its average value. Depending on the magnitude of this gradient, the surface regions of the rolling stock could have a temperature lower than A_{r3}. This is evidenced by the microstructures shown in **Figure 4**, which show the presence of deformed ferrite grains on the surface of the rolling stock, proving the occurrence of intercritical lamination that can explain the occurrence of separations even in the cases where the average finishing temperature was higher than A_{r3}. So, one can deduce that even in the best case within this rolling trial, where the mean finishing temperature was 17°C higher than A_{r3}, was not good enough to warrant a full austenitic finishing rolling.

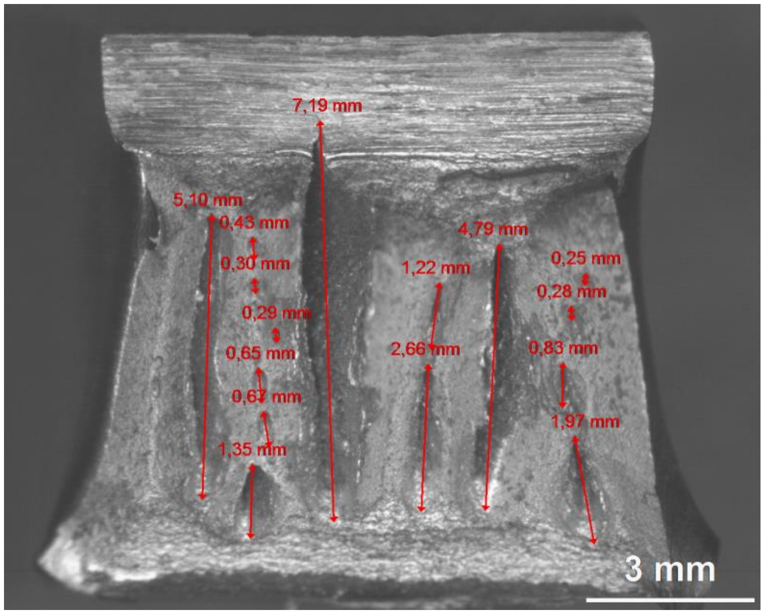
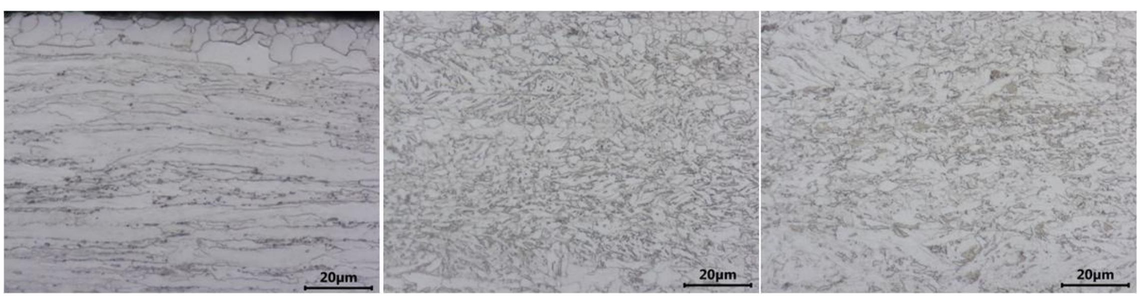


Fig. 3 – Fracture surface of a Charpy specimen broken at -60°C. Several separations can be seen, as well their length measurements. This specimen was extracted from a rolling stock finished at a temperature 22°C below the Ar_3 point of the steel.



(a) Surface (b) ¼ Thickness (c) Center

Fig. 4. Microstructures of 80 ksi grade plates of MnNbTiVCrMo microalloyed steel finished at a temperature 17°C higher than Ar_3. One can note the presence of strain hardened ferrite in the surface of the rolling stock. Nital 3% etch.

The results of the measurements of separation lengths in the fractured surfaces of broken Charpy specimens can be seen in the four graphs of **Figure 5**. As shown in Figure 5a, the minimum separation measured length value in the fractured surface of the Charpy specimens decreased as Charpy test temperature was reduced, as shown in Figure 5a. The specimens extracted from the rolling stock with minimum average finishing temperature showed the shortest minimum separation length, but the effect of finishing temperature was not so clear when this parameter was slightly higher than A_{r3}. It is interesting to note that, according to **Table 3**, the shorter the minimum separation length was, the greater was the number of separations counted in the fractured surface which, consequently, also increased with the lowering of the Charpy test temperature. A similar tendency was also detected as the average finishing temperature was lowered, particularly for the Charpy tests done at -60°C. So, both lower Charpy test temperatures and a increasingly degree of intercritical rolling apparently promote the nucleation of a greater number of separations during the fracture of the Charpy specimen. However, such enhanced nucleation of separations is likely to promote a stress relief in the specimen, depleting the energy that would be required for the propagation of the separations, and thus keeping them short.

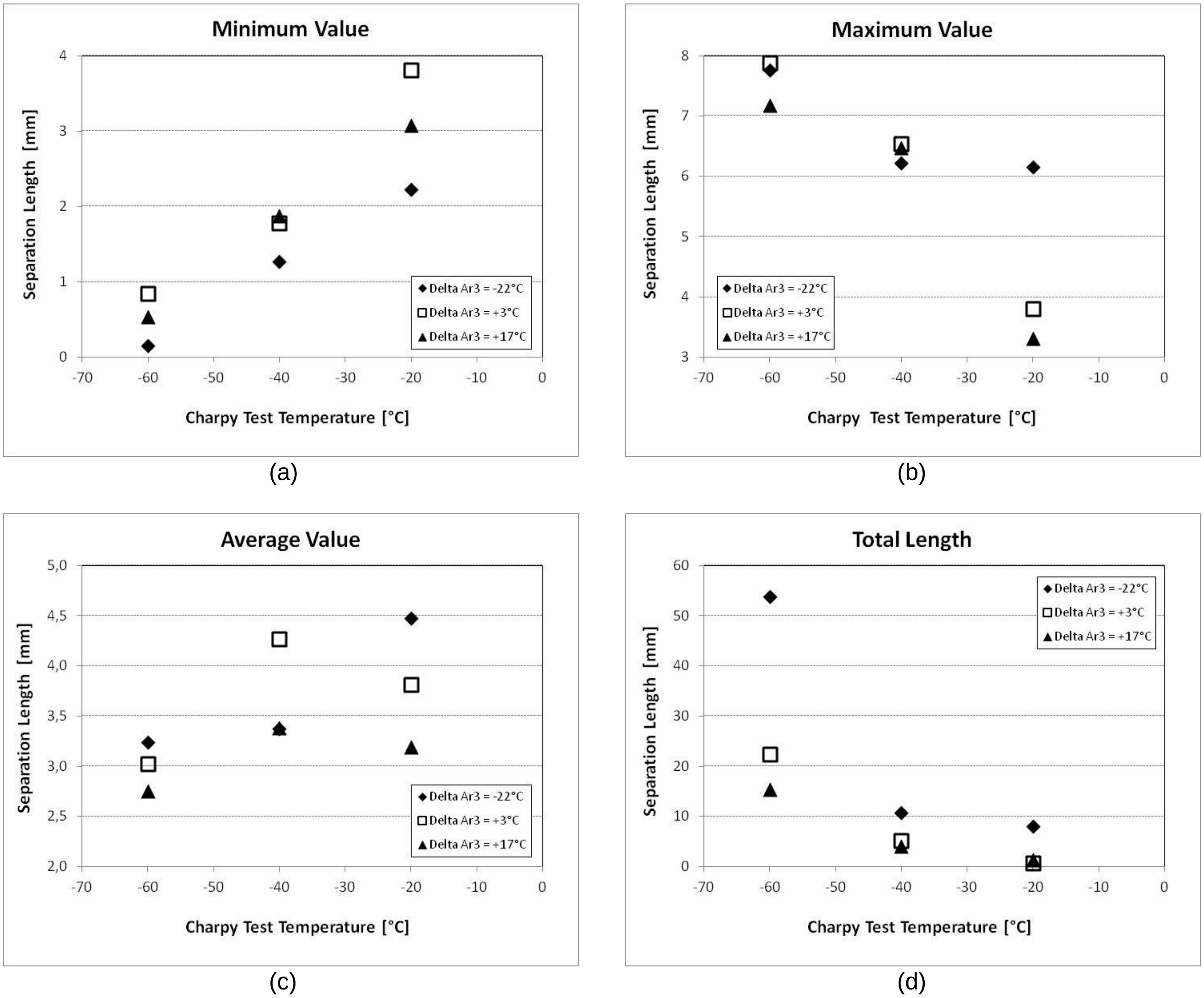


Fig. 5 – Results of the measurement of the separation lengths classified by the difference between the average finishing temperature and A_{r3}, as well the temperature of the Charpy test: (a) minimum length value; (b) maximum length value; (c) average length value; and (d) total length.

Total Number of Separations			
ΔA_{r3} [°C]	Charpy Test Temperature [°C]		
	-60	-40	-20
-22	83	16	9
+3	37	6	1
+17	28	6	2

Table 3 – Total number of separations present in the fractured surface of the Charpy specimens. It must be noted that three specimens were tested for each experimental condition according to average finishing temperature and Charpy test temperature.

For its turn, the maximum separation length increased as Charpy test temperature decreased, as can be seen in Figure 5b. The effect of finishing temperature was not so clear for lower Charpy test temperatures (that is, -60 and -40°C), but became evident for the tests performed at -20°C, with greater values of maximum separation lengths as the average finishing temperature is lowered, specially for the minimum value for this parameter. So, one can conclude that lower Charpy test temperatures and a higher degree of intercritical rolling promoted the propagation of some preferential separations, probably those located in regions with favorable crystallographic texture (Ghosh 2017).

The average value of separation length did not show a clear correlation, neither with Charpy test temperature, nor with average finishing temperature, as is shown in figure 5c. Apparently, in a roughly way, the average separation length tends to increase with the rise of the Charpy test temperature, but data show great dispersion and some inconsistency, which is reflected in the relatively high values of percentual standard deviation shown in **Table 4**. But this fact could be expected, as Charpy test temperature showed contradictory effects on the extreme values of separation lengths: minimum separation length decreases with lower Charpy test temperatures (Figure 5a), while maximum separation length shows an opposite trend (Figure 5b). So, the net effect of Charpy test temperature over average separation length (Figure 5c) is a balance between these two conflicting trends.

Mean Length of Separations [mm], Standard Deviation [mm/%]			
ΔA_{r3} [°C]	Charpy Test Temperature [°C]		
	-60	-40	-20
-22	3.2 (2.4/75)	3.4 (1.9/56)	4.5 (1.6/36)
+3	3.0 (1.7/57)	4.3 (1.8/42)	3.8 (0/0) (*)
+17	2.8 (1.4/50)	3.4 (1.8/53)	3.2 (0.2/6)

(*) Only a data point

Table 4 – Mean length of separations, along with its absolute and percentual standard deviation, present in the fractured surface of the Charpy specimens. It must be noted that three specimens were tested for each experimental condition according to average finishing temperature and Charpy test temperature.

Finally, Figure 5d shows that the lowering of both Charpy test temperature and average finishing temperature increases the total length of separations - that is, the summation of all separations present in the Charpy specimens. This increase was specially high in the case of the rolling stock processed with the highest degrees of intercritical rolling – that is, a minimum average finishing temperature, namely 22°C below the A_{r3} temperature calculated by Ouchi (1982).

The following rolling trial with this steel, where the difference between average finishing temperature and A_{r3} was between +53 and +63°C, showed absolutely no separations in the fractured surfaces of the Charpy specimens, regardless of the temperature used in the test. This proved that the differences between the finishing temperatures and the A_{r3} point of the steel adopted in the prior experiment were insufficient to ensure that the entire rolling stock was completely austenitic at the end of rolling. The mechanical properties of the plates produced in this other trial were also completely satisfactory according to the 80 ksi grade specifications.

Conclusions

The results got in this work show the success of this first implantation for the production of 80 ksi thick plates through controlled rolling and accelerated cooling in the new plate mill of the Gerdau Ouro Branco works. A bridgehead was thus established to initiate the commercial delivery of such material. In addition, the experience gained will allow the technological improvement of this class of products, as well as the advance towards even more sophisticated materials and that meet much more severe demands. The occurrence of separations can be totally avoided provided the average finishing temperature is maintained sufficiently above the A_{r3} point in order to keep the surface of the rolling stock full austenitic, compensating for the unavoidable thermal gradients and inaccuracies arising from the calculation of A_{r3} through an empirical formula.

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