INFLUENCE OF ACCELERATED COOLING CONDITIONS ON MICROSTRUCTURE AND FLATNESS OF API STEEL HEAVY PLATES*

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Abstract
Usiminas Steel Plant in Ipatinga installed an accelerated cooling device named CLC (*Continuous On-Line Control*) in 2010, enabling it to supply steels produced by TMCP (Thermo Mechanical Control Process) technology. This technology complements the TMCR (Thermo Mechanical Control Rolling), with the inclusion of the accelerated cooling process after controlled rolling. There are various gains in terms of quality and productivity associated to the application of such technology. However, the flatness control for API steel becomes crucial because large thermal stresses may be generated due to thermal heterogeneity during the fast cooling when the austenite phase decomposes mostly into ferrite and bainite. In literature, there is lack of knowledge regarding a full understanding of the relation among cooling conditions and plate flatness. Therefore, this work has focused on the effect of the cooling strategy for API steels, aiming at optimizing flatness and keeping the mechanical properties within the specified ranges. The starting point was dilatometer simulation, where cooling conditions such as start cooling temperature, SCT, finish rolling temperature, FRT, and cooling rate, CR, were changed in order to evaluate their effect on microstructure. Those laboratory conditions supposed to give the best results were transposed to industrial scale, so as to produce experimental lots of plates with five different cooling strategies. It was shown the possibility to find a cooling profile that guarantees the balance between mechanical properties and flatness requirements. The influence of cooling strategy on flatness was explained by the varied heat transfer regimes occurring from hot steel surface to the ambient.
Keywords: *TMCP, Accelerated cooling, API steels, Microstructure and flatness*.

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1 INTRODUCTION

The use of accelerated cooling in heavy plate lines began in the early 1980s, initially in Japan and soon thereafter in Europe(1-4). Until 2010 this technology was not used in Brazil. In 2010, the first accelerated cooling equipment for heavy plates in Brazil, called CLC (Continuous on-Line Control), was installed in the Ipatinga plant, as shown in Figure 1.

Figure 1. CLC Equipment of Usiminas

The CLC equipment allowed to supply the new demands of the Oil and Gas Industry, producing steels by means of controlled rolling followed by accelerated cooling, TMCP (Thermo-Mechanical Control Process), instead of TMCR (Thermo-Mechanical Control Rolling).

The technology TMCP presents advantages not only for the users of heavy plates, but for the producers as well, such as lower alloy, reduction of reheating furnace fuel and reduction of electric energy in the rolling mill, additionally to increase the productivity[5-7].

However, one disadvantage of the process is related to the flatness control, once it is common the occurrence of warps in the material after the accelerated cooling process. This condition is related to the stresses generated during cooling, a phenomenon well known for materials produced in offline heat treatment furnaces, but still little discussed for plate produced by TMCP.

This undesired quality result normally requires material rework in a cold leveling process, increasing the production costs and postponing the product delivery. The published literature available does not present enough information to solve this problem and only solutions suitable to specific conditions of accelerated cooling equipment are discussed[8-10]. Due the particularities of each equipment, besides the general characteristics of a Plate Mill, it is hard to generalize solutions that cover all plate producers. This motivates the investigation in this subject, with application more focused in materials produced in the CLC equipment.

The aim of the present work was to investigate the effect of accelerated cooling variables, such as cooling strategies and water flows, in the microstructure, mechanical properties and flatness of API-X70 steel plate. In this way, this investigation sought to increase the knowledge concerning the interaction of these two variables and its effect on the metallurgical and mechanical behavior of this steel, generating subsides to optimize the industrial process.

2 MATERIAL AND METHODS

2.1 Material used

The study was performed with 12 slabs of the material API-X70, from 3 different heats produced in the Usiminas Ipatinga Steel Making plant.

The slab thicknesses were 252 mm. Chemical compositions were according to API 5L specification for line pipe, as shown at Table 1.

Table 1. Chemical composition according to API 5L specification (% in weight) [11]

C	Si	Mn	P	Nb +V +Ti
≤ 0.12	≤0.45	≤ 1.70	≤ 0.025	≤ 0.15

Slabs were rolled for final dimensions of 25 mm x 1511 mm x 12450 mm (thickness x width x length). Each slab rolled generated 2 plates, making a total of 24 plates produced.

2.2 Simulation of cooling curves with different strategies

In a first stage it was selected different strategies suitable to be applied at this studied steel processed via CLC, aiming the improvement of the plate's flatness. With these strategies, the simulations of cooling curves were performed using the laboratory CLC simulator developed for this purpose(12). All tests were performed at 25mm thick API-X70 steel plate. Input data for simulation (process temperatures and flows), are shown in Table 2. Five different strategies were used (E1, E2, E3, E4 and E5), modifying basically the water flow at accelerated cooling equipment. The CLC equipment has 6 cooling zones.

Table 2. Temperatures (ºC) and flows for each cooling zone ($m^3.m^{-2}.min^{-1}$) used in the simulation. FRT: Finishing Rolling Temperature; STC: Start Temperature of accelerated Cooling; FTC: Finish Temperature accelerated Cooling.

Strategy	FRT	STC	FCT	Start	Finish
E1	<760	<730	<500	Low	High
E2	<760	<730	<500	Moderate	Moderate
E3	<760	<730	<500	High	Low
E4	<760	<730	<500	High	-
E5	>800	>780	<450	High	High

It is worth to point out that the E5 strategy considers the accelerated cooling starting from a microstructure totally austenitic, differing significantly from the others, when the cooling starts from a biphasic field.

2.3 Dilatometry with deformation

The dilatometric tests were performed in a Bähr Dil 805D dilatometer which is equipped with a deformation module. The thermomechanical cycle applied is shown in Figure 2 and the values of the applied variables are shown in Table 3.

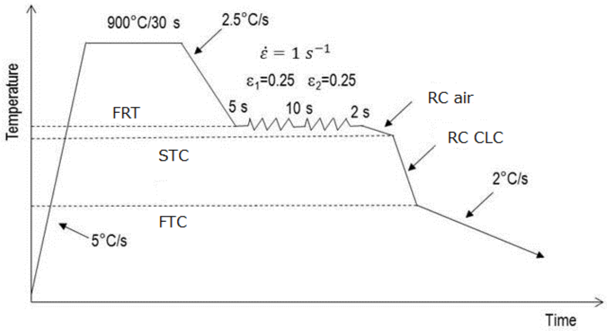


Figure 2. Thermomechanical cycle applied in the dilatometric tests with deformation

Table 3. Parameters of dilatometer tests with deformation. On strategy E3 mod2, the specimen was cooled down in two steps.

Strategy	FRT (°C)	STC (°C)	FCT (°C)	RC ar (°C/s)	RC CLC (°C/s)
E1	<760	<730	<500	0.5	<40
E2	<760	<730	<500	0.5	<40
E3	<760	<730	<500	0.5	>40
E4	<760	<730	<500	0.5	>40
E3 mod	<760	<730	<500	0.5	<40
E3 mod2	<760	<730	<500	0.5	>40/<30
E3 mod3	<760	<730	<500	0.5	>50
E5	>800	>780	<450	0.5	<45

It was performed two deformations in the finishing temperature aiming to condition the austenite, according with the conclusions of Manohar(13), which showed the convenience of using two smaller deformations instead of only a high deformation. The CLC cooling rate was obtained from the CLC simulation results with the conditions of Table 2. Tests were performed applying the five strategies of Table 2, plus three variants of them as shown in Table 3.
The tested specimens were longitudinally sectioned by its diameter aiming the microstructure observation by means of Optical and Scanning Electron Microscope (SEM), after standard metallographic preparation and 4% nital reagent etching.

2.4 Industrial Processing

Since the results of the microstructure analyzes indicated the feasibility of applying different cooling strategies to the industrial process, 12 plates of the steel were industrially processed by TMCP.
The final rolling temperature and accelerated cooling start and end temperatures are shown in Table 4.

Table 4. Cooling strategies at CLC.

Strategy	Sequence	FRT (°C)	STC (°C)	FTC (°C)
E1	01, 02	<760	<730	<500
E2	03, 04	<760	<730	<500
E3	05, 06, 07	<760	<730	<500
E4	08, 09, 10	<760	<730	<500
E5	11, 12	>800	>780	<450

Strategies E1 up to E4, the finishing and cooling start temperatures are in the biphasic region, while in the E5 strategy, the temperatures are in the austenitic region.

2.4.1. Microstructures and mechanical properties

Samples were cut from plates according to the scheme of Figure 3 for analysis of microstructure, tensile properties and toughness.

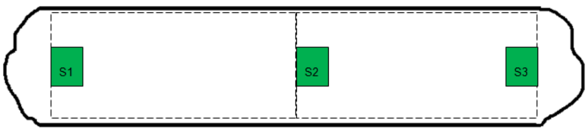


Figure 3. Sampling representation

S2 samples of sequences 02, 04, 07, 10 and 12 were obtained for characterization of the microstructure and observation of the remaining scale layer in longitudinal sections in the body of the plate.
Samples were subdivided into the thickness and embedded preserving their upper and lower surfaces in order to allow the remaining scale to be visualized on both sides, since the thickness of 25 mm exceeded the maximum height of the inlay bakelite.
The microstructure was observed by Optical Microscopy and SEM.
All the plates were sampled to verify the tensile and toughness results.

2.4.2. Flatness Evaluation

Initially the thermographic condition of the plates at the exit of the CLC was evaluated. In the inspection line the plates had their flatness checked with the use of ruler and wedges to indicate the leveling values. The values obtained were compared to the material supply specification. Figure 4 illustrates the flatness measurement activity.

Figure 4. Flatness measurement

3 RESULTS

3.1 Cooling curves

Based on values found in the accelerated cooling simulator, cooling curves were generated for the evaluated strategies, from E1 to E5, as shown in Figure 5. The temperature shown refers to the ¼ position of the plate thickness, which approximates well with the average behavior of the material in the cooling. For the E1, E2, E3 and E4 strategies, the cooling started below 730 °C and finished below 500 °C. For E5 strategy, the cooling started above 780 °C and finished below 450 °C.

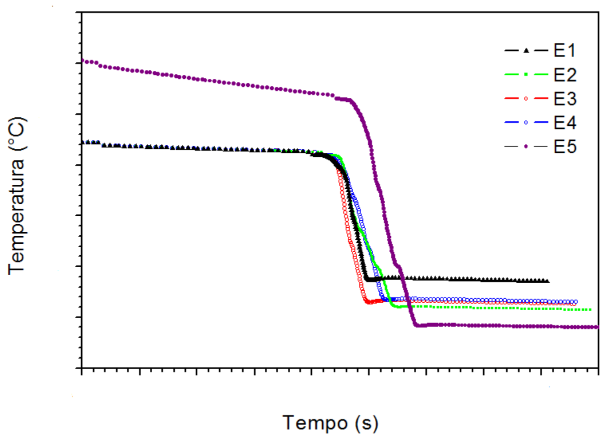


Figure 5. Cooling curves in different strategies of water flow in the zones

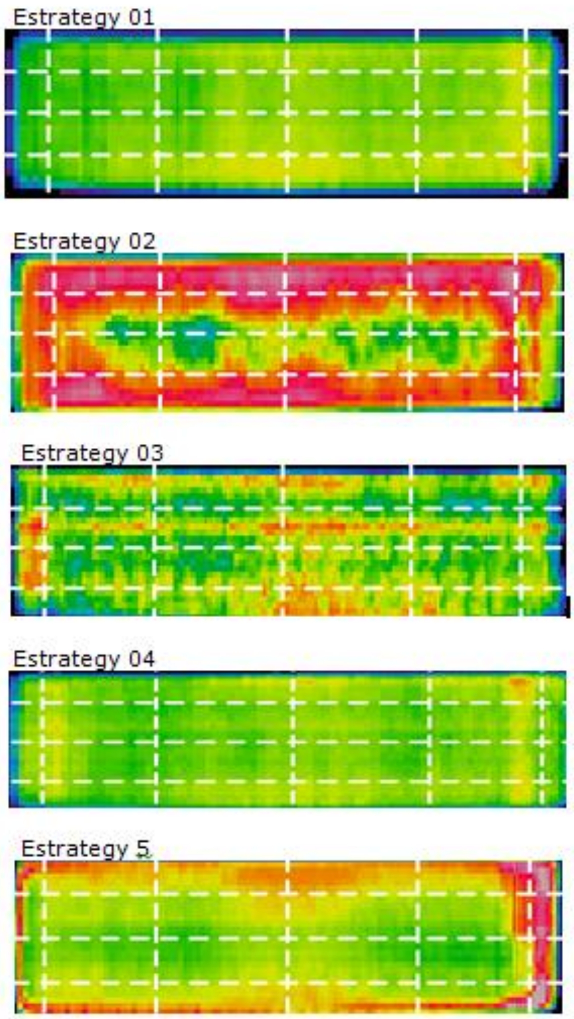


Figure 6. Thermography images of cooled plates according to the strategies studied

3.2 Thermographic Results

For each strategy used, there was an associated thermographic condition. The temperature variation along the length and width of the material was analyzed to correlate with flatness. Figure 6 shows the thermographic results for each cooling condition.

3.3 Microstructure of the industrial plates

Figures 7 and 8 show the microstructure found at ¼ of the thickness of the plates 002, 004, 007, 010 and 012, which were cooled with the strategies from E1 to E5 respectively.

At plate E1, close to the surface, the microstructure was refined and consisted of deformed ferrite grains, and banded bainite. At ¼ of the thickness the microstructure was thicker and there was polygonal ferrite grains and deformed grains, in addition to bainite. Such characteristics shown that the deformation in the finishing pass occurred below Ar_3 as expected and the lower temperature on the surface of the plate relative to the center caused a larger amount of deformed ferrite.

At plates 004, cooled according to E2 strategy, was found similar microstructure for those E1 cooling strategy.

At plate 007, cooled according to the E3 strategy, the microstructure was also composed of deformed ferrite and bainite at the surface and grains of polygonal ferrite coexisting with deformed ferrite, in addition to bainite, at ¼ of the thickness. Apparently, the amount of deformed ferrite at ¼ of the thickness was greater than in E1 and E2 strategies.

The microstructure of plate 010, cooled according to E4 strategy, was formed by deformed ferrite and bainite at the surface and polygonal ferrite, deformed ferrite and bainite at ¼ of the thickness. It can be seen the presence of some deformed ferrite grains close to the surface and the quantity of polygonal grains at ¼ is larger than in the E3 strategy.

Finally, the microstructure in the sample of plate 012, cooled according to E5 strategy, was predominantly bainitic and was obtained with the fast cooling from the austenitic field, with a rate close to 43 °C/s.

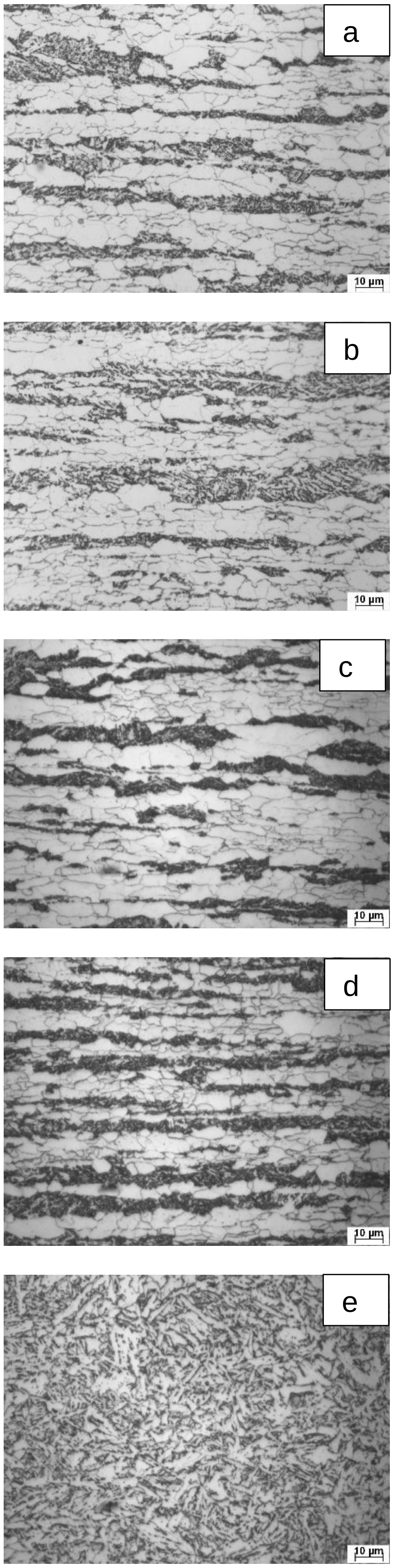


Figure 7. Microstructure seen in the optical microscope with magnification of 1000X to ¼ of the thickness. a) E1 strategy; b) E2 strategy; c) E3 strategy; d) E4 strategy; e) E5 strategy

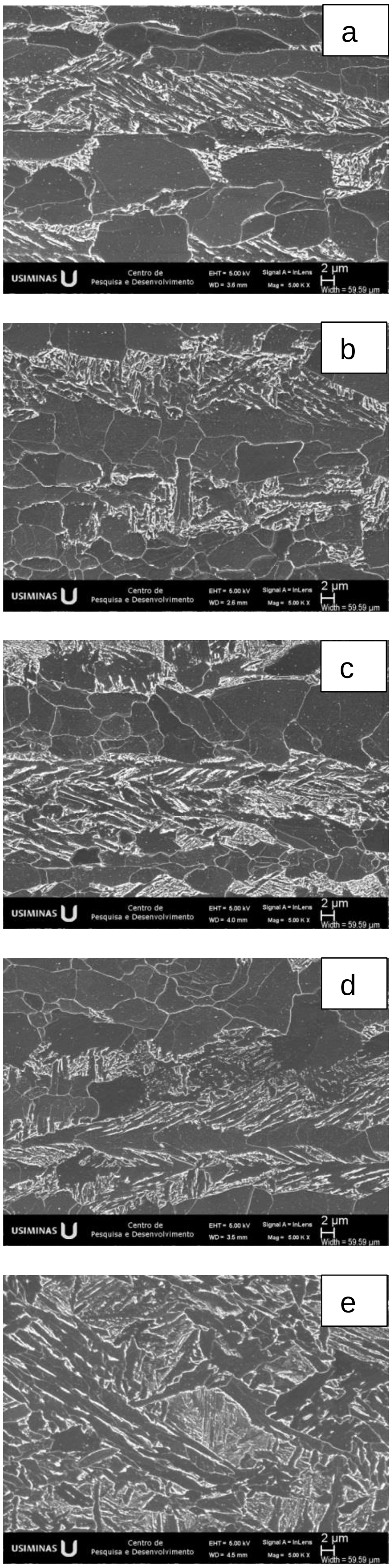


Figure 8. Microstructure seen at SEM to 1/4 of the thickness. a) E1 strategy; b) E2 strategy; c) E3 strategy; d) E4 strategy; e) E5 strategy.

3.4 Tensile Properties

The yield strength, tensile strength and elongation results are shown in Figures 9, 10 and 11, respectively. It is observed that the lowest tensile strength result was obtained with the E3 strategy. Strategies E1 and E2 presented similar results, in intermediate position. The highest values were obtained for the strategies E4 and E5. For elongation, all the results met the specification, without significant variation between them. Therefore, from the point of view of increasing mechanical resistance such strategies are indicated.

It should be highlighted that the E5 strategy has higher finishing temperature, which favors the rolling process.

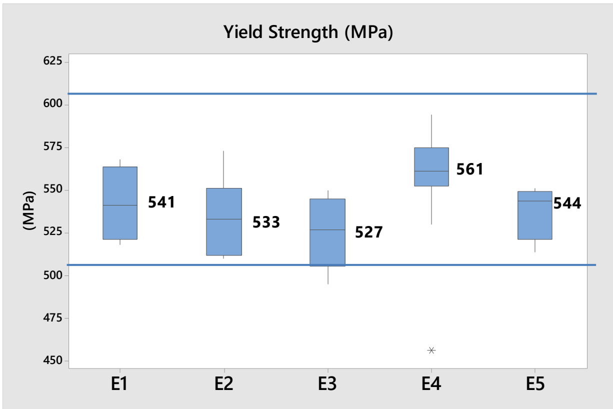


Figure 9. Yield Strength obtained in each strategy

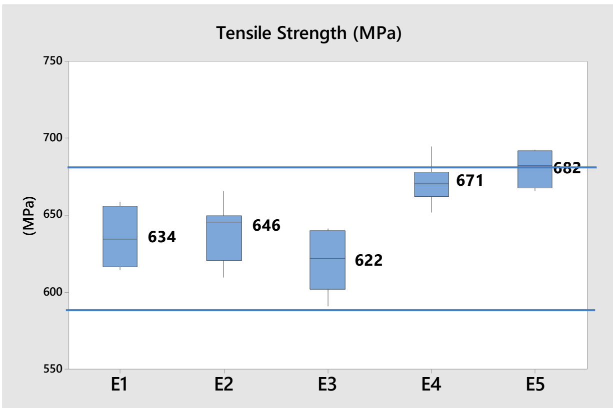


Figure 10. Tensile Strength obtained in each strategy

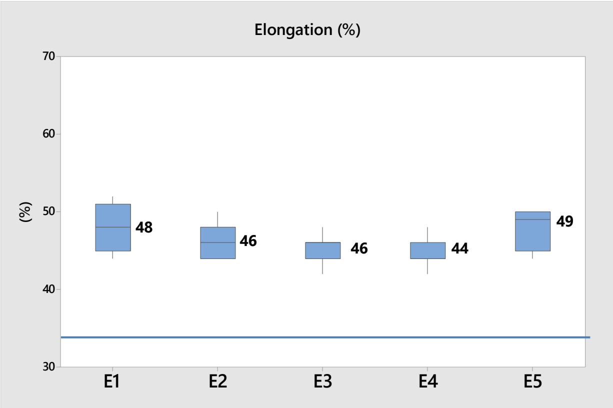


Figure 11. Elongation obtained in each strategy

3.5 Toughness

The DWTT and Charpy impact tests were performed at -20 °C temperature. Specimens were taken from the plate in a transverse direction. Figure 12 show the percentage of ductile fracture in the DWTT, given by the average of 2 specimens tested for each rolled plate. It was observed that for E5 strategy decreased in the percentage of ductile fracture.
However, based on the Charpy results shown in Figure 13, where the energy absorbed for the E5 strategy is comparable to the other strategies, it can be stated that there was an inverse fracture[14], which would invalidate the estimated ductile fracture value and, as a result, the test. The results of both DWTT and Charpy show that the steel is very tenacious and that, from the point of view of toughness, all strategies tested could be used.

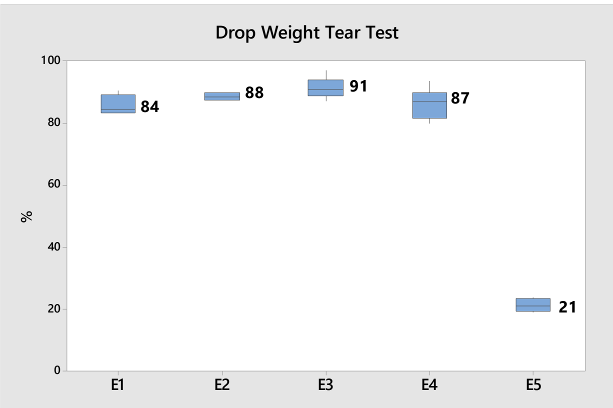


Figure 12. Percentage of ductile fracture in DWTT in each strategy

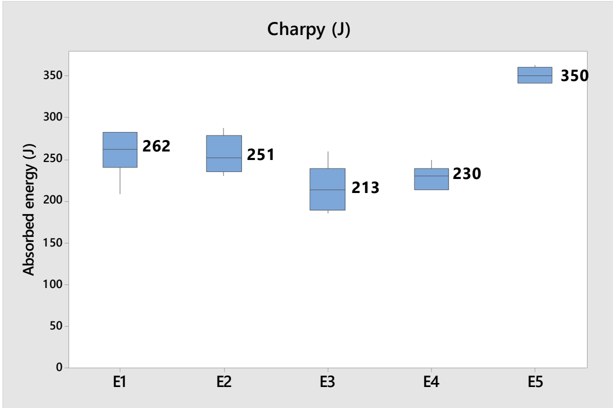


Figure 13. Absorbed energy in Charpy CVN tests in each strategy**.**

3.6 Flatness

All plates were inspected and had their flatness checked. The results are shown in Figure 14. The general feature of flatness is warping at the ends of the plates in a convex shape. Note that for the E2 strategy there is a worse flatness result, which is consistent with the fact that this strategy presented greater thermal heterogeneity.

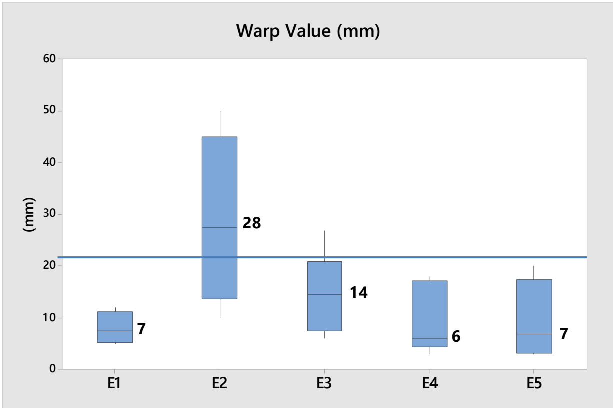


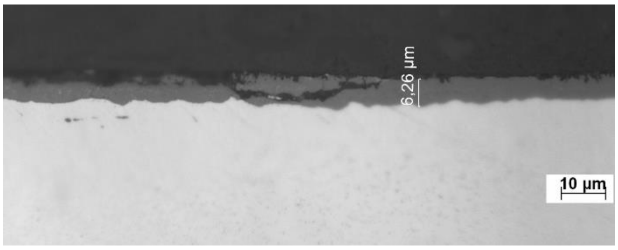
Figure 14. Warp values found for each strategy

3.7 Scale found in industrial plate samples

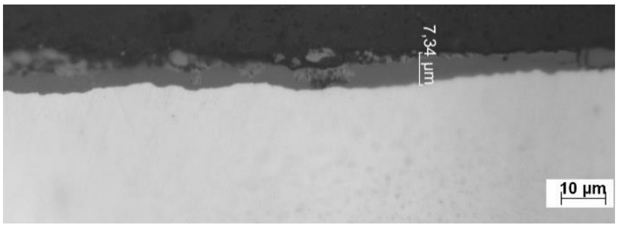
The analysis of the scale present in the plates after accelerated cooling was limited, as the water jets cause partial detachment and its degradation. This analysis focused in the sites with preserved scale, evaluating the condition of the scale thickness.

Figure 15 shows images of the scale layer present on the upper surface of the plates for the strategies used. At low finishing temperatures (E1 to E4), the thicknesses of the remaining scale ranges from 6 µm to 9 µm. It was evident that in the samples related to the strategies E2 and E3 the scale was more degraded than the others, which is consistent with the greater thermal heterogeneity shown in the thermography in Figure 6.

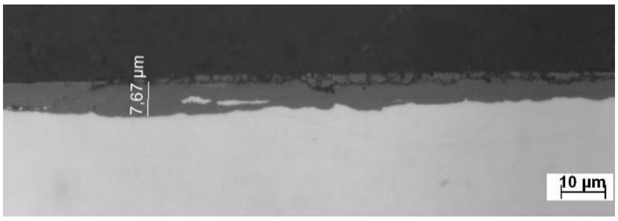
In the plate material with high finishing temperature, E5 strategy, the scale layer thickness was 23 µm in the places where it was preserved, as expected. However, this greater thickness did not influence significantly the uniformity of cooling.



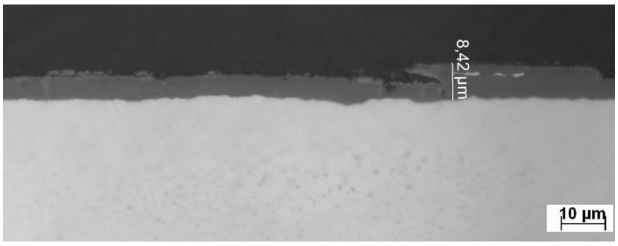
(a) E1



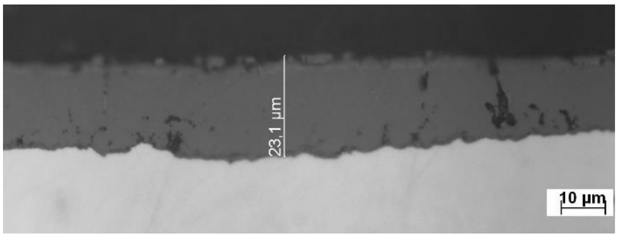
(b) E2



(b) E3



(c) E4



(d) E5

Figure 15. Scale layer in the upper surface of the plates, in each cooling strategy

4 DISCUSSION

From the microstructural point of view, the strategies of E1 to E4 presented similarities, being constituted by deformed and polygonal ferrite grains and bainite at ¼ of the thickness. This is due to rolling strategies and accelerated cooling starting in the biphasic region.

For the E5 strategy, with the rolling being all in the austenitic region and the beginning of the cooling also in this phase, the microstructure was predominantly bainitic, with a cooling rate close to 40 ºC/s.

In terms of the yield strength, considering the strategies from E1 to E4, the highest values were for E4 strategy, whose rolled plates were submitted to fast cooling speeds, near 40 °C/s, using high flow rates in the first 4 zones of the accelerated cooling.

The E5 strategy resulted in higher strength values, with some samples exceeding the specification limit of APIX70 steels. It is observed that the yield strength was not as affected as the tensile strength in this strategy.
The toughness evaluated by Charpy tests indicates that all strategies presented high results of absorbed energy, the E5 strategy presenting the highest toughness.
In terms of thermal homogeneity, the E1 strategy presented the best result, and the E2 strategy, the worst. It is noted that the cooling rate in the two conditions was the same, what differed is that the E1 strategy used a lower cooling rate in the beginning of the CLC, increasing in the last zones, while the E2 strategy used a cooling schedule with the same flow for all areas.
The difference in thermography can be explained by the different heat transfer regimes(14) that occur during the cooling of a hot plate with water. A longer time in the nucleated boiling region causes an irregular cooling(15), Figure 16, which is perceived by the thermography image.

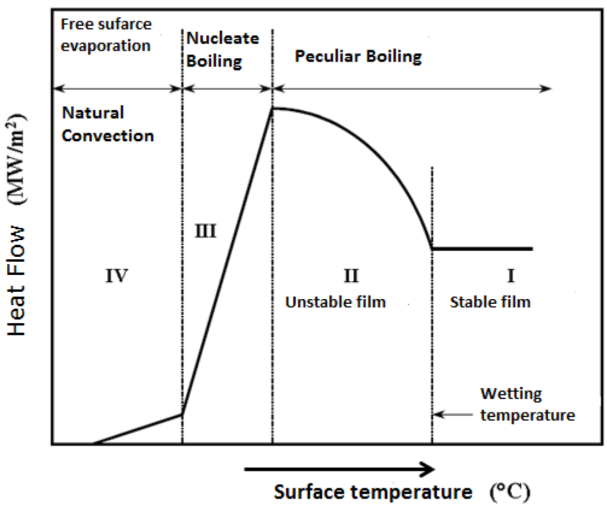


Figure 16. Schematic representation of the boiling curve of water on the surface of a heated plate(15)

The heterogeneous temperature condition after accelerated cooling reflected on flatness results. As shown in the results of the warp measurement, the E2 strategy, which presented the highest temperature variation, also presented the worst flatness, which can be attributed to the tensions generated by the non-uniform cooling.
Strategies E3 to E5 presented satisfactory flatness results according to the specification. The E2 strategy plates were recovered by cold leveling.
Thus, it is possible to state that, with the exception of E2 strategy, all other strategies meet the specifications of mechanical properties and flatness, with E5 strategy being the best overall.
Adjustments to the quality design can be made by reducing alloys, reducing the manufacturing cost of the boards and also making the rolling process more productive with the E5 strategy. Thus, the accelerated cooling equipment of Usiminas, which has modern control conditions, fulfills its role of achieving steels with higher tensile requirements and higher toughness.

5 CONCLUSION

The different cooling strategies tested showed a significant effect on the mechanical properties, especially the tensile strength, and the flatness of the rolled plates.
Among the five strategies evaluated, four were adequate for the production of API-X70 steels complying with the standard specifications.
When the finishing temperature occurs in the biphasic region, the final microstructure contains deformed ferrite, as expected, in addition to polygonal ferrite and bainite. High values of mechanical strength and toughness can be obtained depending on the cooling strategy.
In the strategy with finishing temperature and cooling starting in the austenitic field, the microstructure was basically bainitic, and the tensile and toughness properties were high, without compromising the flatness of the final products.
The thermal homogeneity of the rolled plates is closely related to its flatness condition, therefore it is a factor of constant search for improvement.

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