EFFECT OF PLATE SURFACE QUALITY ON THE EFFECTIVENESS OF THE ACCELERATED COOLING PROCESS*

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Abstract

Controlled rolling followed by accelerated cooling, known worldwide as TMCP, aims to increase mechanical properties without toughness deterioration. The process principle is to promote the plate cooling with water jets along the range of the austenite transformation temperatures. The accelerated cooling process is only fully effective when controlled in an integrated manner, as it alone cannot ensure significant improvements in the final properties of steels. Plate surface quality depends on some parameters that must be controlled before the start of the plate accelerated cooling. Good flatness is essential to avoid irregular water accumulations during cooling. After the reheating process, the slab should have uniform temperature, uniform austenitic grain size and easily removable scale. The slab thermal and microstructural heterogeneities are inherited by the rolled plate and tend to increase further during the accelerated cooling. This results in flatness problems, high level of internal stresses and mechanical property variations. The descaling strategy is an extremely important factor and must be determined with great caution. It is important that scale thickness and distribution is uniform to ensure homogeneous cooling over the entire plate surface. Otherwise, there will be an uneven temperature distribution, which can cause serious problems of flatness, surface quality and mechanical properties.

Keywords: Plate mill; TMCP; Scale, Flatness, Accelerated Cooling.

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1 INTRODUCTION

The accelerated cooling process requires that scale surface formation is uniform so as not to prejudice the homogeneity of plate temperature throughout the rolling process, from slab reheating until the forced cooling with water. Non-uniformity of scale thickness affects directly the final shape and mechanical properties of the plate. It is essential that in all stages of the production process that there is a uniform temperature evolution, starting with the slab reheating and, from this, a controlled decrease of the temperature of the plate in the rolling and cooling stages.

This homogeneity can only occur if all heat transfer conditions occur without the interference of an insulating scale layer which is non-uniform in its formation or removal from the plate surface. The scale formation, to be suitable during the heating process, requires that there is a permanent control in the process parameters of the reheating furnace. Thus, it is important to control the total heating time of the slabs, the temperatures of each zone and the internal atmosphere in the reheating furnace. The basic rule for this process is not to allow excessive heating time, which is achieved by obeying the best heating curve, based on mathematical models that allow the best thermal soaking in all slab dimensions. Another parameter to be controlled is the maintenance of the air / fuel ratio, which must be as stable as possible for the fuel used, passing from a slightly reducing initial atmosphere in the first zones to a somewhat oxidizing atmosphere in the final zones of the reheating furnace, not allowing oxygen excess inside of the furnace.

Thereafter, following the discharging and primary descaling, it is necessary to ensure high efficiency in the scale removal that forms on the plate from the furnace exit until the beginning of the accelerated cooling.

In order to do this, the descaling should be strictly controlled and consistent through the pass schedule, design and maintenance of the right descaling nozzles, adjusting the best relative positions of height and attack angle of each descale header, and correctly positioning the respective nozzles. Currently, there are state of the art nozzles with high impact force values, which aid in the secondary and tertiary scale removal in the rolling.

In the Gerdau Ouro Branco’s Plate Mill there are controls that work through the mathematical models of the reheating furnace to optimize the slab heating. This aims to reduce excessive formation of the primary scale and reducing adherence to the slab surface which makes it more difficult to remove in the descaling steps. The Ouro Branco plate mill has the most modern descaling system, with strategically placed high pressure and impact nozzles. There is also an automatic descaling strategy during the pass schedule, but it can be actuated manually by the operator, if necessary. After the mill there are a pre- leveler and an accelerated cooling machine called MULPIC (multi propose interrupted cooling) [1].

This integrated system greatly reduces the scale formation prior to the accelerated plate cooling process, allowing the plate to exhibit the most suitable characteristics in terms of final flatness, so as not to allow mechanical properties to exhibit significant variations over the three dimensions of the final plate.

This work will show the performance results and controls that are performed during TMCP.

2 INFLUENCE OF THE SCALE ON HEAT TRANSFER

The surface scale layer that forms during the rolling process is thermally insulating, which causes different cooling conditions throughout the plate as a function of the heat transfer phenomena that occur during each step of the hot rolling process.

Several previously published studies [2-5] have shown that the scale and its physical characteristics, such as thickness, shape and adhesion, results in different values of heat transfer coefficient in the plate during the accelerated cooling process.

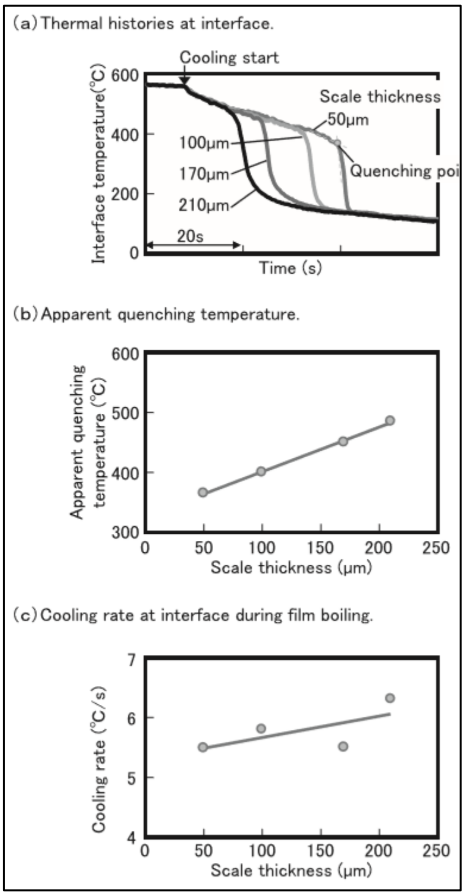


Figure 1. Effects of scale thickness on spray cooling characteristics (scale type Al2O3, water flow density 0.00167 m^3/m^2s) [2].

Scale thickness will add a thermal insulating layer which prevents heat loss and reduces the heat transfer coefficient during air cooling [3]. Figures 1, 2, 3 and 4 show experimentally that the thickness and the roughness of the scale influence the cooling rates and the surface temperatures achieved by the plate. This happens due to the different coefficients and heat fluxes that are produced in the presence of the scale [2].

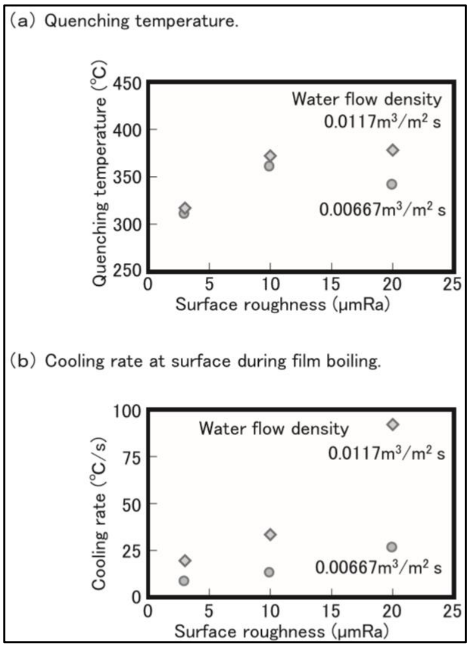


Figure 2. Effects of surface roughness on spray cooling characteristics (Non-coating) [2].

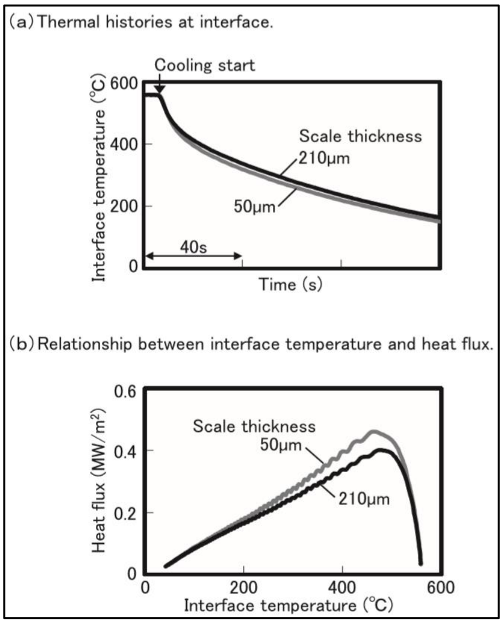


Figure 3. Effect of scale thickness on air jet cooling (scale type Al2O3, Air flow density 3.83N m^3/m^2s) [2].

Figure 5 shows how the scale thickness changes the heat transfer coefficient and, therefore, the surface temperature of the plate during spray cooling [3]. Greater scale thicknesses promote strong variations in the corresponding heat transfer coefficients along a broad surface temperature range. So, mother plates showing different surface scale thicknesses can have different local cooling rates which can lead to temperature heterogeneity.

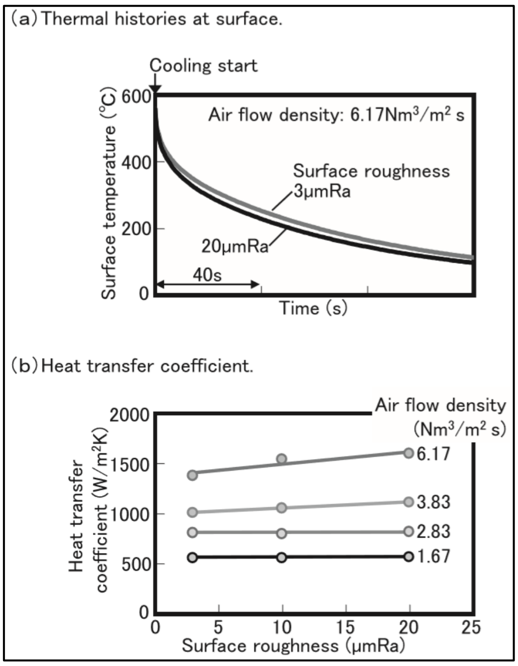


Figure 4. Effect of surface roughness on air jet cooling (Non-coating) [2].

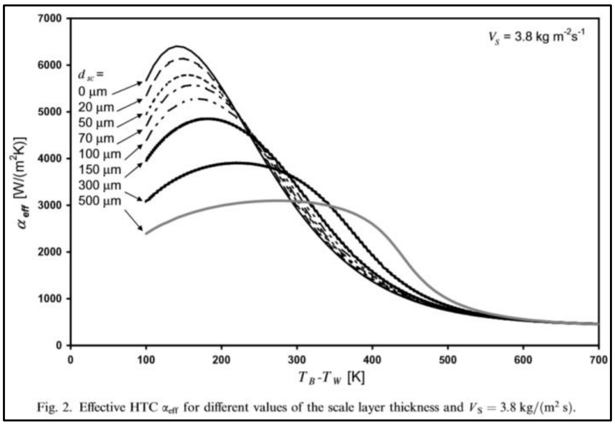


Figure 5. Effective HTC αeff for different values of scale layer thickness and Vs=3.8 kg/(m².s) [3].

The cooling capacity of water during the accelerated cooling of a steel plate at high temperature shows a characteristic behavior defined by the so called boiling curve, Figure 6. Kadoya et al [6] explained that "in the high temperature region, a stable steam vapor film is formed between the steel plate and the water, causing a state termed as film boiling and, despite a high temperature in the region, the cooling capacity becomes slightly lower".

Hyungdae et al [7] showed that when a liquid droplet is placed on a surface held at a temperature much higher than the liquid's boiling point, it hovers on a vapor cushion without wetting the surface. This phenomenon is called film boiling and occurs at surface temperatures beyond the so-called "Leidenfrost point (LFP)." If the surface temperature is at or above the LFP, heat transfer from the surface to the liquid takes place by conduction and radiation through the vapor layer, and thus the liquid takes a significantly longer time to evaporate than it would on a surface held at lower temperature.

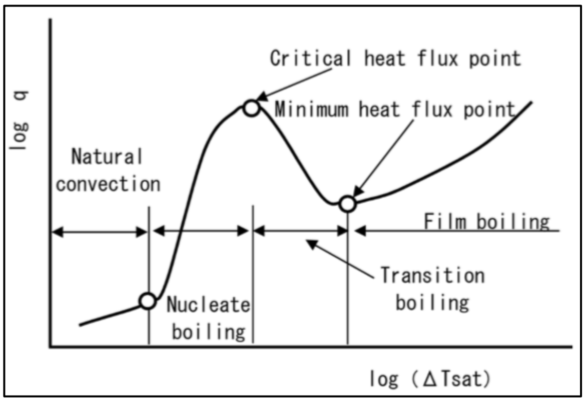


Figure 6. Boiling curve of water [6].

Kadoya et al [6] explained that "As the steel plate temperature goes down, contacting of water with the steel plate starts and, as the steel plate temperature further goes down, the area of contact of water with the steel plate expands and the state of cooling enters the transition boiling region where the cooling capacity increases. As the temperature of the plate further goes down, the state of cooling goes into the nucleate boiling region where bubbles generated play a major role. In cooling steel plates, cooling in the transition boiling region is crucial. In this region, as the cooling capacity increases along with the decrease in plate temperature, uneven temperature distribution within a steel plate developed in the earlier cooling is enlarged and, finish cooling temperature also varies for each steel plate”.

Figure 7 shows how scale can interfere with the steam layer during cooling. Scale can shift the Leidenfrost temperature from film boiling to transition boiling and interrupt and break up the film boiling steam layer and help to initiate the movement to transition boiling [7].

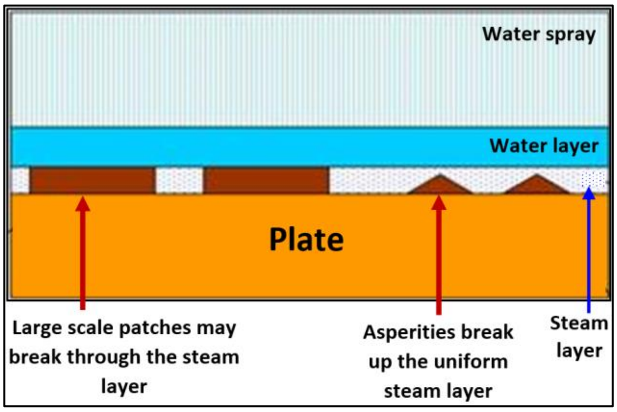


Figure 7. Scaled or uneven plate surface.

Lee [4] stated that the surface roughness of the plate, which is influenced by the scale formation, changes the phenomenon of heat transfer in the accelerated cooling process of the plate. Generally, the rougher the surface, the higher the Leidenfrost temperature. A rough surface also increases the surface contact area with the water under the cooling nozzle and a rough scale will increase the nucleation site for steam bubbles to form for nucleate boiling [5].

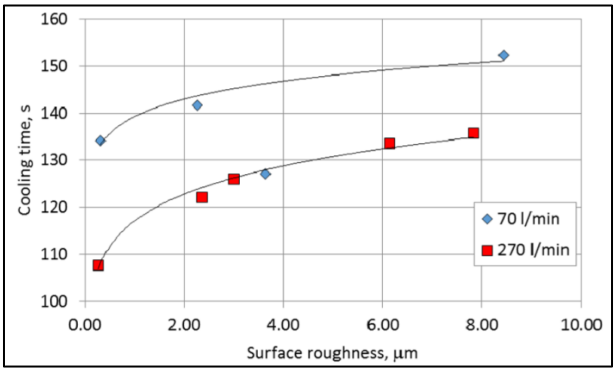


Figure 8. The effect of surface roughness on the time to cool the plate from 700°C to 100°C for parallel flow cooling with two different flow rates [5].

The effect of the roughness on the cooling efficiency was proven experimentally by Prodanovic et al. [5], where increased roughness led to an increase in plate cooling time between 700° C and 100° C, as shown in figure 8. In this example roughness is quite small, and it could be that the Leidenfrost temperature increases but the peak heat flux reduces as in figure 5.

As it is shown the scale/ water and heat transfer are clearly a complex phenomenon.

Flatness is influenced by austenite transformation which is also related to temperature, as it is not instantaneous, and the austenite decomposition products have different specific weights than the original phase. This is the origin of residual stress in the plate, and the resulting strain depends on the formed constituents: pearlite/ferrite mixture, bainite and martensite [8,9]. Figures 9 and 10 [9] show the volume change and the consequences of tensile stresses.

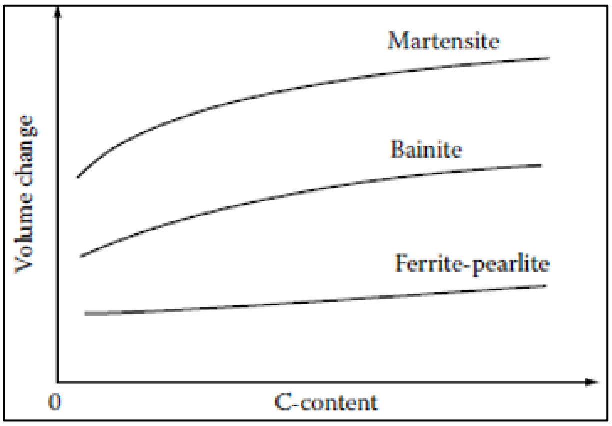


Figure 9. Volume changes vs. carbon contents of plain carbon steel due to martensitic, bainitic, and ferrite-pearlitic transformation (schematically) [9].

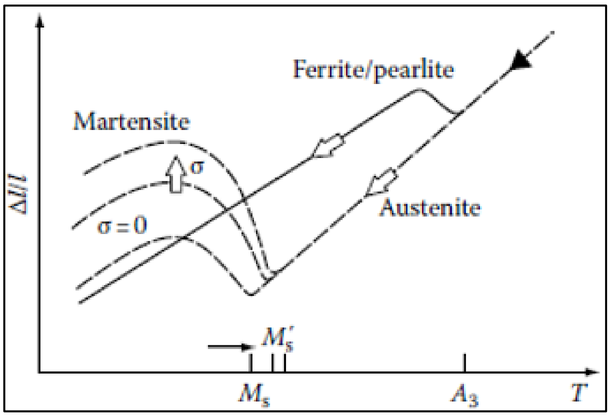


Figure 10. Consequences of tensile stresses on the relative changes of length during rapid cooling of austenitized steel specimens compared with slow cooling behavior [9].

Figure 11 [10] show at a cooling finishing cooling temperature target of 670°C the temperature is close to the point where the phase change finishes and there is a change in the coefficient of thermal expansion at this point. A higher plate temperature will cause a shorter length. Figure 12 [11] show other example of the increasing in length with transformation from austenite to martensite. It will affect directly the final plate flatness and internal stress.

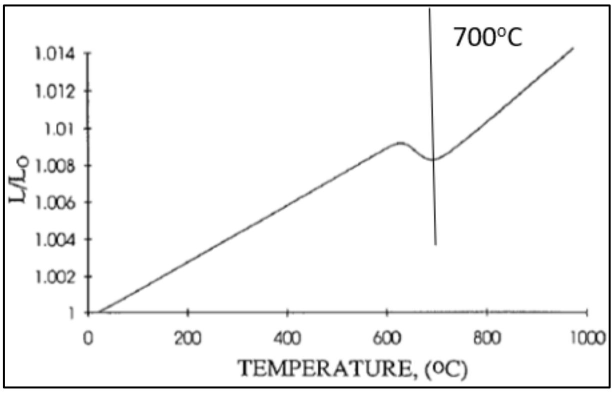


Figure 11. Computed dilatation curve for an AISI 1010 steel. L0 is the original length and L is the current length [10].

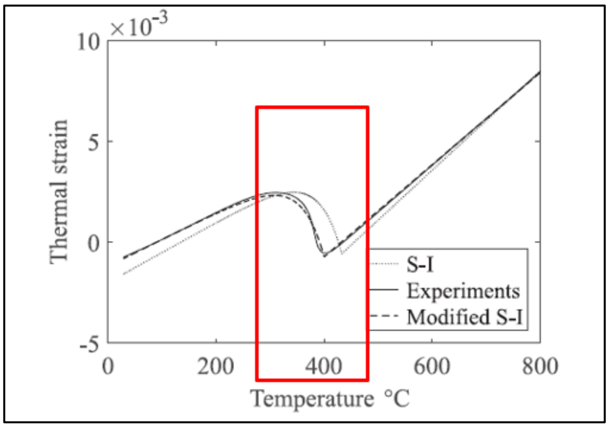


Figure 12. Models and experimental curves of phase transformation from austenite to martensite in Hardox 450, a low alloyed carbon steel [11].

The emissivity of the scale influences the temperature measured by the pyrometer which has a single emissivity set for a clean scale free steel surface so the apparent surface temperature can be different from the actual.

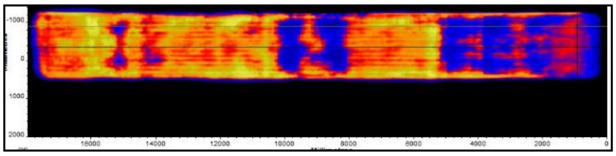
The objective of this study was to evaluate the influence of surface scale formed during the rolling process on the performance of the accelerated cooling process.

3 MATERIAL AND METHODS

Several plates were rolled in the Gerdau Ouro Branco Plate Mill Line. Secondary descaling strategies were changed during the finishing rolling phase.

Figure 13 shows the surface temperature distribution after the accelerated cooling performed under different descaling strategies. The dark regions have lower temperatures, which probably are covered with thicker scale.

(a) Thermographic image with heterogeneous scale.



(b) Thermographic image with homogeneous scale

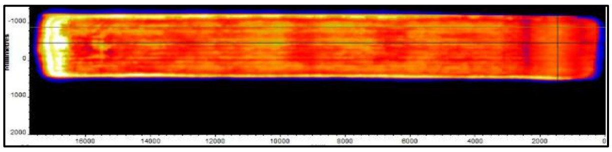


Figure 13. Thermographic image of the mother plate after accelerated cooling, with (a) heterogeneous scale and (b) homogeneous scale.

Figure 14 shows the region of a plate where non-uniform descaling occurred due to the absence of a descaling nozzle. Samples were taken from this location for metallographic and mechanical analysis.

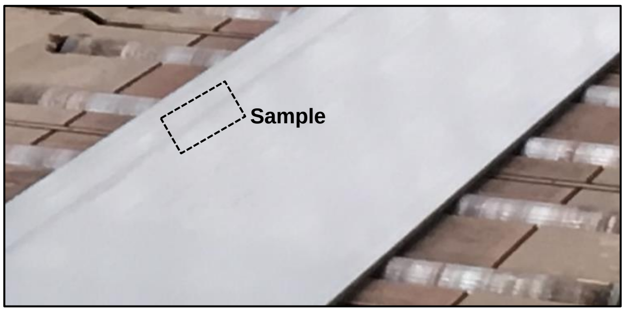


Figure 14: Plate with not uniform descaling.

Figure 15 shows the visual appearance of the upper face of one of these samples, showing the interface between fine (at left) and coarse (at right) scale. It can be observed that the roughness of the surfaces between the two scales morphologies are different.

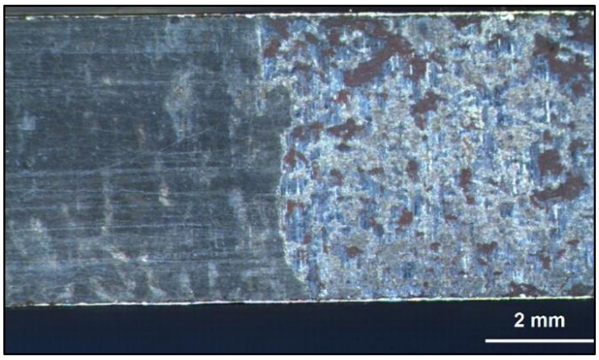
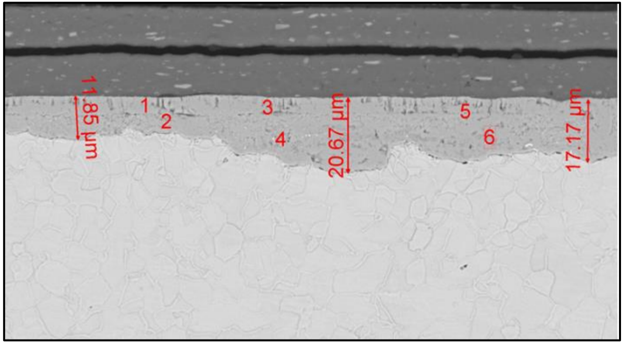


Figure 15: Visual appearance of the upper face of the fine scale and the coarse scale.

Figure 16 (a and b) shows the cross sections of thin and coarse scale, including their thicknesses at several points.

(a) Thin scale



(b) Coarse scale.

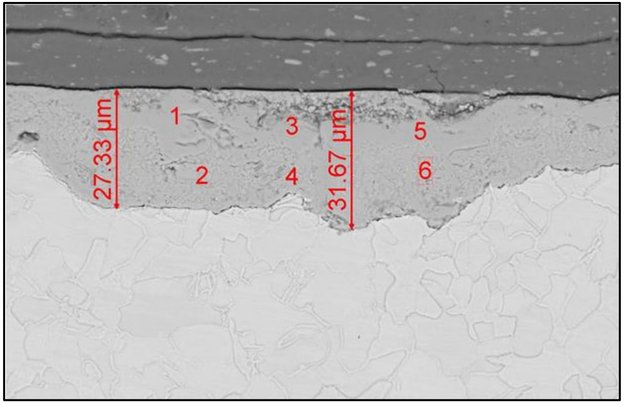


Figure 16: Image obtained by scanning electron microscopy of the cross section in the samples with (a) thin scale, e (b) coarse scale.

Table 1 shows the results from the tensile tests obtained from samples extracted in the regions with fine and coarse scale. It is possible to observe that the sample with coarse scale obtained higher values of yield and tensile strength, as well elongation.

Table 1. Tensile test result in the sample with fine and thick scale.

Sample	**Yield Stress 0.5% [MPa]**	**Tensile Strength [MPa]**	**Elongation**
Fine Scale	**414**	**487**	**58**
Coarse Scale	**427**	**527**	**62**

Figure 17 shows an example of the finishing accelerated cooling temperature variation and the corresponding tensile strength values along the length of a mother plate centerline. It is observed that the tensile strength is inversely proportional to this temperature and that the variation of this last parameter probably comes from the scale non-uniformity.

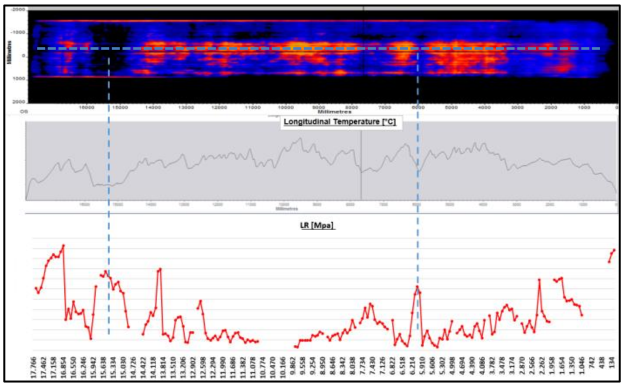
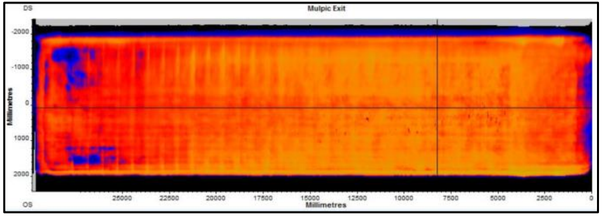


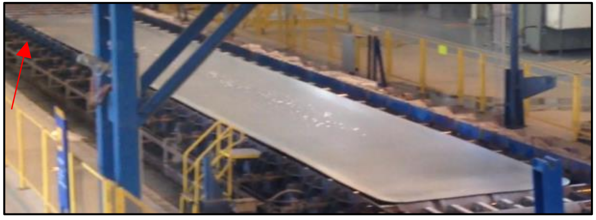
Figure 17: Variation of the tensile strength as a function of the final cooling temperature in a plate with heterogeneous scale distribution.

Figure 18 (a, b, c, and d) shows the final shape of a rolled plate with the scale on its tail. The plate showed flatness defects in the tail after exiting the accelerated cooling machine. The plate showed good flatness at the hot leveler exit but, as it remained in the cooling bed, the flatness defect reappeared.

(a) Thermography after accelerated cooling.



(b) Plate after accelerated cooling.



(c) Plate after hot leveler.

(d) Plate after air cooling at the cooling bed exit.

Figure 18: (a) Thermographic image of a mother plate that showed scale located at the tail, (b) the same plate after accelerated cooling with flatness defect at the tail, (c) showing good flatness at the tail after hot leveler, and (d) showing flatness defect after air cooling.

4 RESULTS AND DISCUSSION

The scale morphology influences final cooling temperature, final flatness and mechanical properties.

The presence of the non-uniform scale on the mother plate surface causes local variations in the values of heat transfer coefficient and heat flows. The regions with thicker scale have higher Leidenfrost temperature. The consequent expansion of the transition boiling range increased the average heat transfer coefficient, thereby increasing cooling rate and reducing the final temperature of accelerated cooling where scale was thicker [2,3].

Therefore, the result is that the finishing cooling temperature varies according to the local scale morphology. This was demonstrated in Figure 7, where the plate thermography carried out after accelerated cooling with a thicker scale shows lower temperatures. Different roughness levels are visually perceived in the regions with coarse scale compared to the rest of the plate.

The values of mechanical strength were higher in the regions with lower finishing cooling temperature and coarse scale, due to the higher values of heat transfer in these regions.

It can also be observed that the flatness was affected. These flatness problems were correlated with the formation of heterogeneous scale. The different temperature gradients generate different residual stress states that remain present in the mother plate after the hot levelling process.

5 CONCLUSION

Scale forming naturally in the hot rolling process influences the final shape of the plate and its final mechanical properties. The efficiency of the accelerated cooling is strongly correlated with the different heat transfer coefficients locally prevailing on the mother plate surface as a result of the variations in thickness and roughness of the scale that occur throughout the thermomechanical treatment. For this reason, a strict control in the production process must be adopted, from the slab reheating to the start of plate accelerated cooling.

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