EFFECT OF COIL COOLING CONDITIONS ON THE OCCURRENCE OF THICKNESS OSCILLATION DURING COLD ROLLING OF A CR-MO ALLOY DP STEEL*

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Abstract
During cold rolling of Cr-Mo alloyed DP steel, considerable oscillation of thickness may occur. The literature points out that such occurrence is due to non-uniform cooling of the coil after the hot rolling process. Since the austenite transformation in this steel continues after coiling, the microstructure and, consequently, mechanical properties are very susceptible to natural variations in cooling rates associated with distinct positions of the coil. The influence of coil cooling conditions on thickness oscillation during cold rolling was evaluated in this work by using both industrial experiments and dilatometer tests. It was verified that an industrial coil presented large variation of mechanical properties associated with its heterogeneous microstructure. Consequently, thickness oscillation occurred during cold rolling. Dilatometer tests simulating hot run-out table and coil cooling showed that the austenite transformation is very slow under small cooling rates that occur after coiling. Thus, the slow transformation rate makes the coil very susceptible to environmental conditions around it during its natural cooling and is responsible for variation in mechanical properties of the coil. To ensure the formation of a more homogeneous microstructure in the whole coil, it is necessary either to make use of technologies that improves the cooling uniformity or to adjust the steel alloy design. The latter alternative has been done with relative success by using conceptions with lower amounts of Cr and Mo.
Keywords: thickness oscillation, cold rolling, Cr-Mo DP steels, coil cooling.

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1 INTRODUCTION

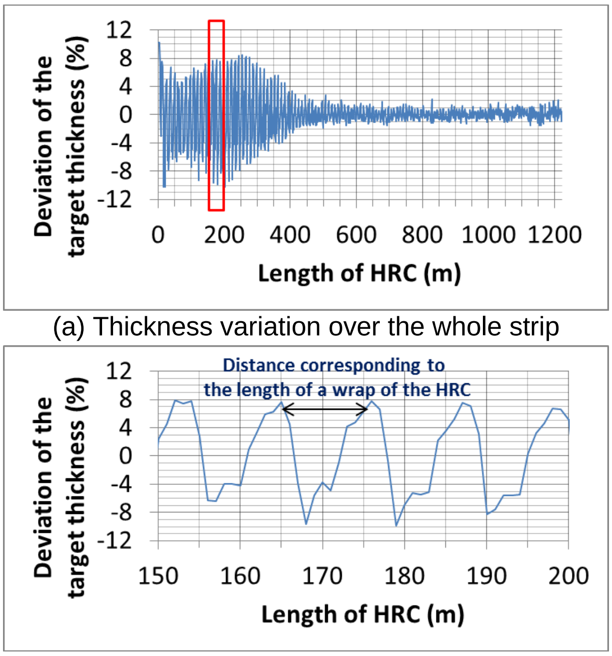
Due to the combination of high strength and good ductility, the advanced high strength steels (AHSS) have been very demanded by the automotive industry, because they allow weight reduction and provide greater vehicle safety. Among them are the dual phase (DP) steels that are characterized by the microstructure composed of a ferritic matrix with a second hard phase, typically martensitic.

The DP steels must have a chemical composition that combines micro-alloying, such as Nb and Ti that favor microstructural refinement, and alloying elements, such as Mn, Si, Cr, and Mo. These alloying have the function of stabilizing austenite, promoting solid solution hardening, favoring the formation of ferrite and, in the case of Cr and Mo, delaying the pearlite or bainite formation [1,2], a need for DP steel production in hot dip galvanizing lines. In these lines, the annealing treatment takes longer (low speed) and has higher final temperatures than in continuous annealing lines, due to the downstream Zn coating process.

For a cold-rolled and coated steel, the final mechanical properties are defined only after heat treatment and coating. However, an appropriate thermomechanical process must be carried out in the hot rolling so that instabilities in subsequent processes, such as thickness oscillation in cold rolling, do not occur.

An example of this thickness oscillation is shown in figure 1 for a Cr-Mo alloyed steel. This oscillation usually occurs in regions near the outermost wraps of the hot rolled coil (HRC), at intervals equivalent to the wrap length.

Poliak et al. [3] and Kaputkina et al. [4] associated this phenomenon with the non-uniform cooling of HRC after hot rolling, especially when the austenite present in the microstructure after the finishing hot rolling does not transform in the run-out table. They explain that after coiling, HRC cools faster in its upper part than in the lower one, producing a harder microstructure in the faster cooling region. Poliak et al. [3] suggest to avoid the formation of ferrite during coil cooling and to increase the extent of austenite to bainite transformation still in the run-out table using lower coiling temperature. This temperature must be reached well in advance to the coiling in order to allow the earlier start of austenite to bainite transformation. As such, less extension of transformation would occur after the coiling.



(a) Thickness variation over the whole strip

(b) Location highlighted in (a)

Figure 1. Thickness oscillation occurred during cold rolling of a Cr-Mo steel.

This recommendation may be unfeasible in the run-out table used in this work because it is short and all cooling banks are normally opened to achieve the target coiling temperature. This makes it difficult to start the transformation before the coiling. Even knowing this possible limitation, the suggestion by Poliak et al. [3] was examined in the present work. Experimentally, some HRCs of Cr-Mo alloyed DP steel with the coiling temperature inside the bainitic field were produced.

The microstructure and mechanical properties at different points of individual wraps of a HRC coiled in the bainitic field where examined, together with the occurrence of thickness oscillation during cold rolling of this strip. In addition, the effect of different cooling rates on HRC microstructure formation was evaluated.

2 MATERIAL AND METHODS

2.1 Industrial Processing and Sampling

Table 1 presents the chemical composition, in nominal ranges, of the steel.

Table 1. Chemical composition of the evaluated steel (mass %)

C	Si	Mn	Al	Nb + Ti	Cr + Mo	B
0.08~ 0.18	0.10~ 0.50	0.80~ 2.00	0.010 ~ 0.090	0.010 ~ 0.080	0.10~ 0.70	0.0030 max.

The strip evaluated in this work was obtained by hot rolling with an average final finishing rolling temperature of 892°C. The coiling temperature ranged from 460°C to 495°C in the last 35 m of the strip, this being the region where samples were taken. Figure 2 shows the sampling positions along the coil length. Eight samples were taken across the outermost wrap (numbered 1 to 8) and four more on a whole wrap about 35 m inwards the outermost ones (numbered 9 to 12).

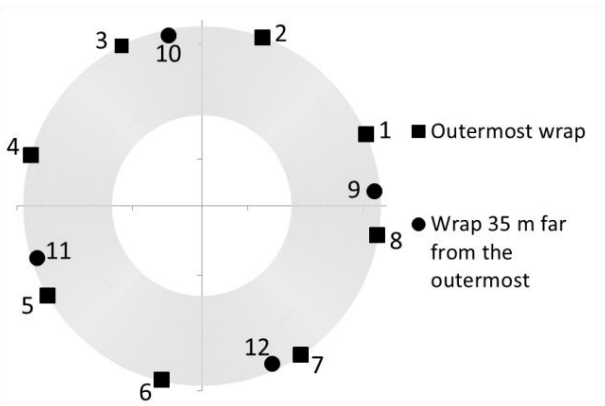


Figure 2. Sampling positions in industrially produced hot rolled coil (HRC).

2.2 Microstructural and Mechanical Properties Characterization of the HRC and Thickness Variation

Tensile mechanical properties were evaluated according to NBR ISO 6982-1 standard [5] in a 10 t Instron 5882 tensile testing machine. These tests were performed on all samples at the following positions: strip edges, called edge 1 and edge 2, at ¼ and ¾ of width from edge 1, and center of the width. Some samples were selected for microstructure and hardness evaluation. Sections in thickness and parallel to rolling direction were prepared according to standard metallography procedures. These were etched with Nital 4% reagent and analyzed by field emission scanning electron microscopy (FE-SEM) ZEISS – Ultra 55® operated at an accelerating voltage of 5 kV and inlens detector. Hardness was determined with 1 kgf load using a Micro-Vickers FM-ARS9000 hardness tester.
Subsequently, another HRC of the same steel processed in the hot run-out table under similar conditions was cold rolled. Its thickness variation was recorded and samples were taken in positions with higher and lower thickness for microstructure analysis purpose.

2.3 Simulation of Coiling and Cooling Conditions

A Bähr DIL805 dilatometer was used to simulate conditions in the run-out table, during coiling and coil cooling. Figure 3 shows the thermal cycles performed during dilatometer tests: (i) heating at 10°C/s to 880°C (final finishing rolling temperature of this steel, FT); (ii) 30 s holding to ensure complete austenitization of the specimen; (iii) cooling to 510°C (coiling temperature of this steel, CT) at rates equivalent to those of the industrial process (CR1); and (iv) cooling at slow rates (CR2) down to the final temperature (Tf).
CR1 value was constant and equals to 31°C/s. Two values for CR2 were

evaluated: 0.05 and 0.005°C/s. In addition, a cycle using constant CR1 until 150°C was performed to determine the start time and temperature of austenite transformation.

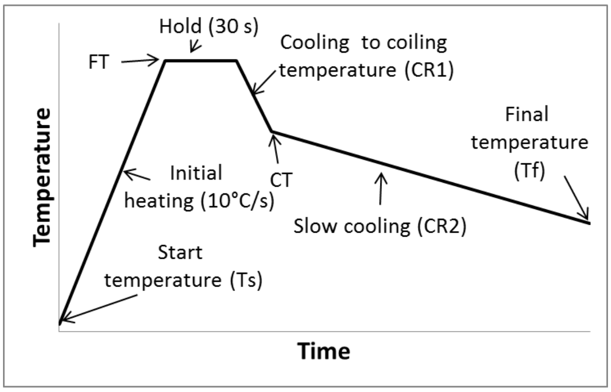


Figure 3. Scheme of the thermal cycles performed by dilatometry.

3 RESULTS AND DISCUSSION

3.1 Industrial Test

Figure 4 shows the mechanical properties along with the outermost wrap of the industrial HRC that was cooled in the bainitic field. It can be noted a large variation in properties. The yield strength (YS) changed up to 310 MPa and the ultimate tensile strength (UTS) up to 180 MPa.

The microstructures were predominantly bainitic with small amounts of ferrite in the edge 1 at positions 4 and 8, and in the center at position 4, as shown in figure 5-a. At the other positions, the microstructure contains larger amount of ferrite, besides the presence of bainite and martensite islands, as shown in figure 5-b. As this part of the coil is normally scrapped before cold rolling, a wrap at about 35 m inwards was evaluated.

Figure 6 shows the mechanical properties for the wrap at 35 m inwards the coil. It can be seen that changes in mechanical properties were smaller: YS varied up to 80 MPa and UTS up to 50 MPa.

The microstructures at points 11 and 12 in the edges and center were composed mostly of ferrite, bainite, and martensite, as shown in figure 7-a. In the center at position 11, there is also fine pearlite, as shown in figure 7-b.

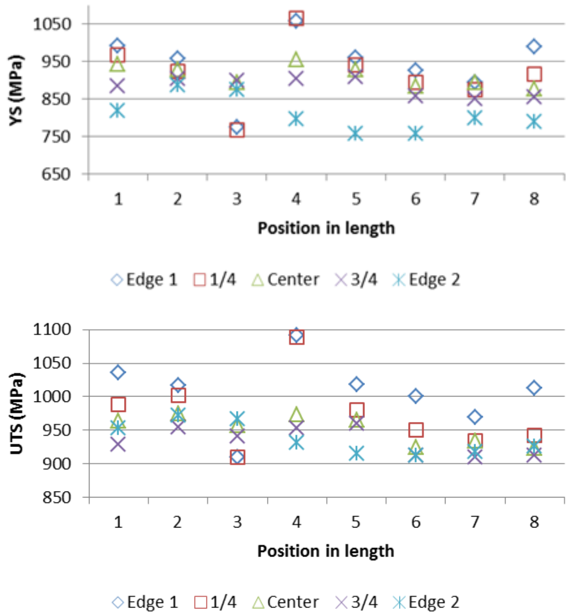
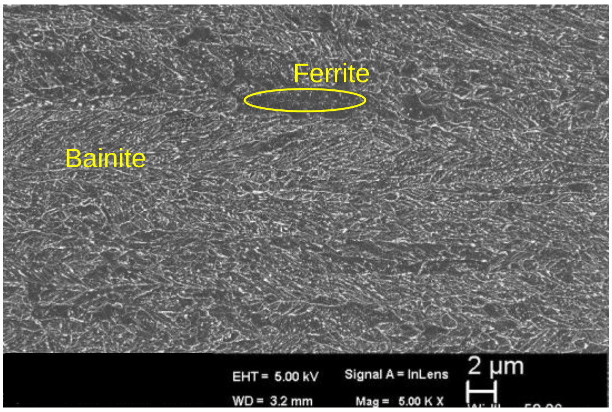
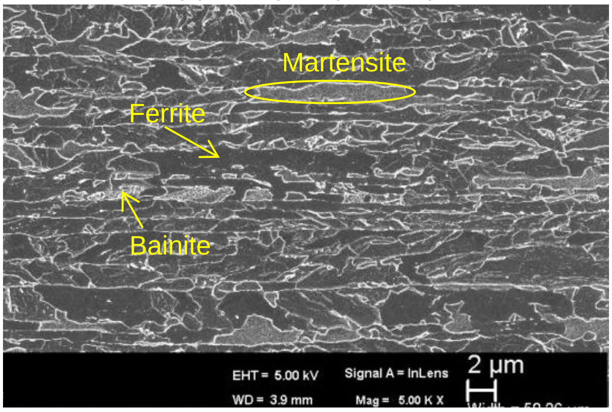


Figure 4. Mechanical properties of the strip along the length in the outermost wrap of industrial HRC.



(a) 4-Edge 1 (387 HV)



(b) 8-Edge 2 (302 HV)

Figure 5. Microstructure of the strip at points 4-Edge 1 and 8-Edge 2.

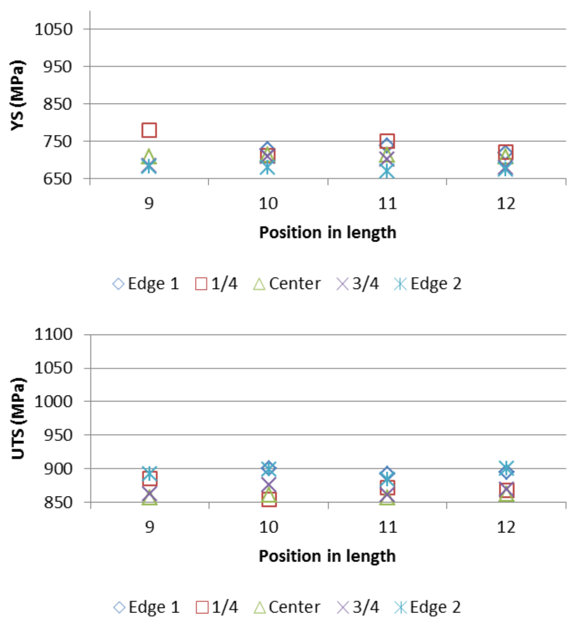
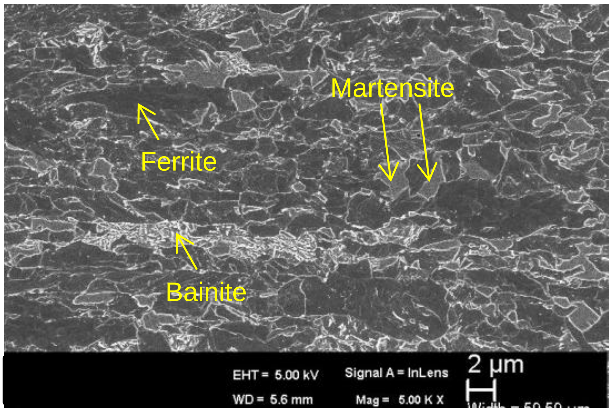
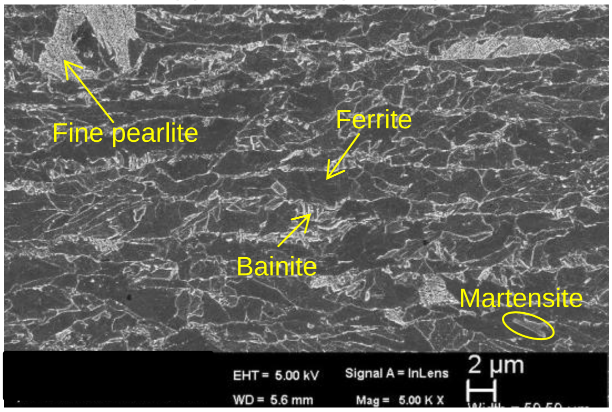


Figure 6. Mechanical properties of the strip along the length in the wrap at about 35 m from the outermost one of the industrial HRC.



(a) 12-Center (233 HV)



(b) 11-Center (274 HV)

Figure 7. Microstructure of the strip at points 12-Center and 11-Center.

The variation in mechanical properties of this strip was rather significant. Even at the wrap 35 m inwards the outermost one, UTS, for example, varied more than 40 MPa, which was the maximum value found by Kaputkina et al. [4] in their study on the same phenomenon.

To explain the large variation observed it is presumed that the austenite transformation did not start before the coiling, because all extension of the run-out table was used to reach the CT in the bainitic field. Therefore, for this hot rolling line, the recommendation of Poliak et al. [3] of increasing the extent of austenite to bainite transformation still in the run-out table was not applicable due to its short length and to the steel chemical composition. Moreover, ferrite formation was not prevented, as small amounts were found in all positions evaluated.

In addition, it was noticed that the inner wrap had a higher amount of martensite than the outermost one, although its cooling rate had been lower. This occurs because of carbon partitioning between ferrite and austenite during phase transformation at low cooling rates. It is well known that carbon diffuses to and enriches austenite, stabilizing it and, so that it can be transformed later into martensite. Some authors have already demonstrated this phenomenon, associating the extent of partitioning with martensite hardness [6-9].

It can be concluded that coiling in the bainitic field may not be much effective to obtain a more homogeneous microstructure in the HRC of Cr-Mo DP steels.

Thickness oscillation during cold rolling (figure 8) was verified in a strip produced under the same conditions of the studied one (CT~510°C).

It was verified that points with high and low thickness within the oscillation had different microstructures (figure 9), being this one more evidence that microstructure heterogeneity is responsible for this phenomenon.

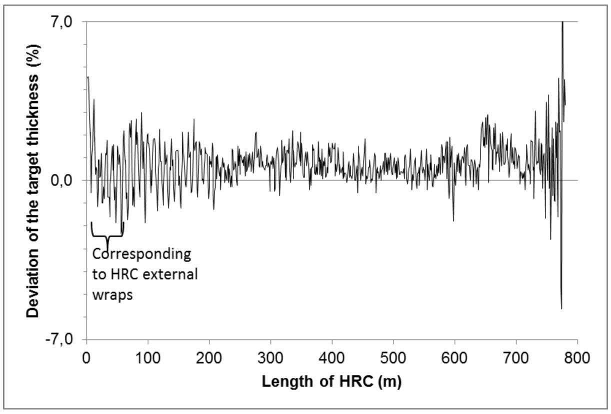
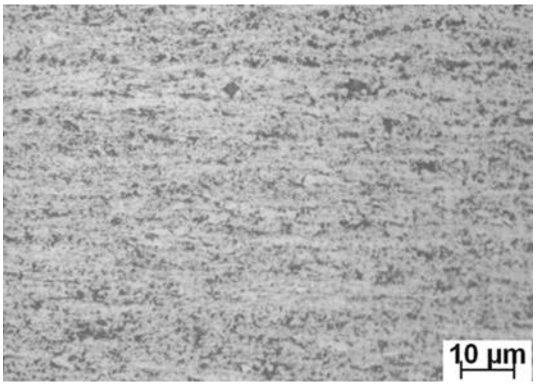
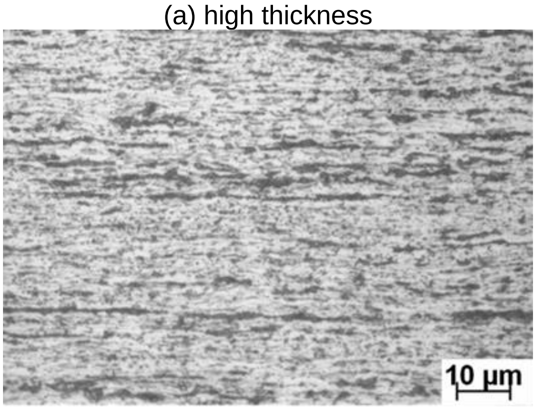


Figure 8. Variation of thickness after cold rolling of the HRC.



(a) high thickness



(b) low thickness

Figure 9. Microstructure at points of high and low thickness within the strip region having thickness oscillation after cold rolling

3.2 Influence of Coil Cooling Conditions on Microstructural Heterogeneity

By dilatometer tests, it was observed that the soaking temperatures evaluated were suitable for complete austenitization of the steel. Ac_1 and Ac_3 temperatures for this steel were, respectively, 731 and 848°C.
In the cycle which only CR1 was applied, the austenite transformation started near 500°C after 12 s of cooling, that is below the CT=510°C. This indicates that no transformation would occur under industrial conditions in this steel during cooling in the run-out table using similar cooling rates. However, in the industrial process, austenite may be partially hardened at the end of rolling, which would favor its transformation at higher temperatures [2], so that a small amount of ferrite could form. The obtained microstructure was composed mainly of bainite and martensite (figure 10).

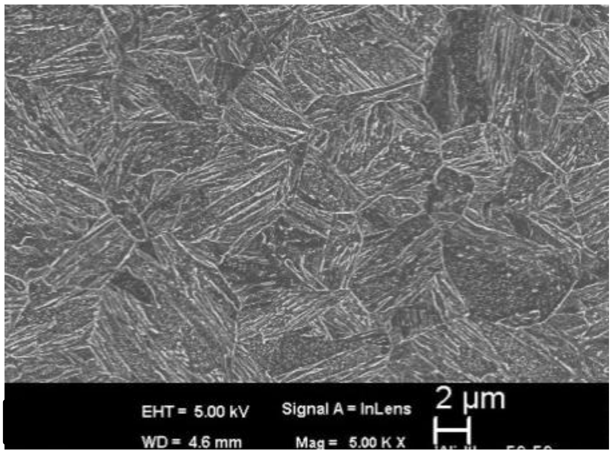
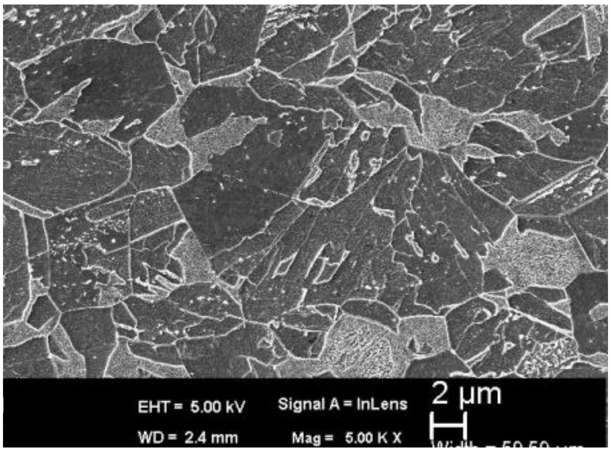


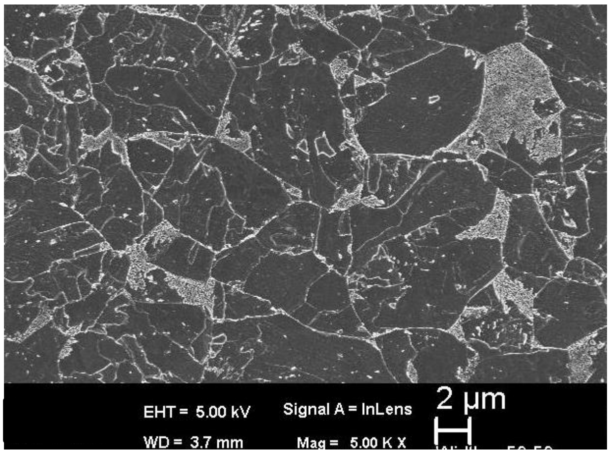
Figure 10. Microstructure for cycle with constant CT1 until 150°C. Average hardness was 403 HV.

In the cycles performed to evaluate the effect of cooling rates of the HRC, it was found that the austenite transformation started few seconds after the change from CR1 to CR2.
In both CR2 used, the microstructure (figure 11) consisted of ferrite with irregular boundaries (formed at lower temperatures) with internal carbides, bainite, and martensite. However, in the cycle with CR2=0.005°C/s there was also the formation of fine pearlite (figure 11-b), as observed at position 11-Center of the industrial coil (figure 7-b). Thus, the hardness variation observed was up to 32 HV. Therefore, it would be difficult to avoid austenite to ferrite transformation when coiling at 510°C.
Kaputikina et al. [4] found differences in hardness up to 10 HV in an industrially obtained coil. The difference obtained by

them is smaller, possibly due to the studied steel, a 22MnB4, which has no addition of Cr and Mo.



(a) Cycle with CR2=0.05°C/s (295 HV)



(b) Cycle with CR2=0.005°C/s (263 HV)

Figure 11. Microstructures for cycles varying CR2.

Concerning the kinetics, the transformation for the cycle with CR2=0.05°C/s finished after 38 min of cooling, while for the cycle with CR2=0.005°C/s, the transformation finished only after 4.3 h.

The tendency of this Cr-Mo alloyed steel to form different microstructures associated with different cooling rates at distinct positions of HRC is due to its very slow austenite transformation kinetics at low cooling rates. The remaining austenite, even after hours of HRC cooling, causes the microstructure to be very susceptible to small variations in local conditions.

The low rate of austenite transformation rate, obtained in cooling at 0.005°C/s can be explained by the partitioning of Cr and Mo during the ferrite formation. Ebrahimian et al. [9] explained that an initially austenitic microstructure when cooled to the temperature field of ferrite formation and being held long at that temperature, carbon and carbide-forming alloying elements such as Cr and Mo accumulate at the austenite/ferrite interface of transformation. This is due to lower diffusivity of these alloying elements in austenite compared to ferrite. Thus, the diffusion of carbon and these alloying elements become so slow that they hamper the migration of ferrite-austenite boundary, reducing its growth rate and stabilizing the austenite kinetically.

For these reasons, it can be concluded that the coiling condition investigated in this work were not effective in obtaining homogeneous mechanical properties. A more suitable alloy design should be sought in order to improve the homogeneity of mechanical properties along the length of the coil. This alternative has been done with success by using lower amounts of Cr and Mo. Another alternative would be to obtain ways to ensure maximum uniformity of HRC cooling by using, for example, thermostatic covers as indicated by Chashchin [10].

4 CONCLUSION

1. Coiling in bainitic field of the Cr-Mo alloyed steel studied was not effective to obtain HRC microstructures with the high homogeneity degree required to avoid thickness oscillation during cold rolling.
2. The relatively slow kinetics of phase transformation, which leads to untransformed austenite in HRC even after hours of cooling, makes the microstructure very susceptible to small variations in environmental conditions close to HRC. This reflects in microstructure and mechanical properties variations along the length of the strip.
3. To overcome the thickness oscillation, it would be recommended to use a

better alloy design that could accelerate the austenite transformation kinetics and also use technologies that ensure more uniformity of coil cooling.

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