EFFECT OF COOLING CONDITIONS AFTER HOT ROLLING ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF A DUAL PHASE STEEL OF 800 MPa STRENGTH*

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Abstract

The effect of the cooling conditions on the microstructure and hardness of a Dual Phase hot-rolled steel 800 MPa strength was investigated. Simulations of the cooling conditions using a dilatometer were carried out from samples of a hot rolled coil with variations of the intermediary temperature from 620 to 740°C, isothermal holding time between 1 and 10 s and coiling temperature between 50 and 400°C. In addition, two CCT (Continuous Cooling Transformation) diagrams were developed to evaluate the effect of the isothermal holding time on the phase transformations of the remaining austenite. It was observed that the intermediary temperature has a strong influence on the kinetics of the phase transformation, as well as the isothermal holding time influences the amount of ferrite formed and, consequently, the final microstructure and hardness of the material. The coiling temperature did not cause significant changes in the amount and morphology of the ferrite, but a gradual replacement of martensite with bainite was observed, which, in addition to the self-tempering effect, contributed to the hardness reduction.

Keywords: *Dual phase steels; Hot rolling; Dilatometry; Cooling conditions.*

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1 INTRODUCTION

In the last decades, the automotive industry has focused its efforts in the search for sustainable changes for society, demanding the development of new materials and processes that allow fuel economy, lower emission of pollutants and increase vehicle safety. This has stimulated the development of various types of steels that are not only more resistant but also have better formability characteristics for the mass production of vehicle bodies and components. The application of high strength materials is a frequently used strategy enabling weight reduction of automobiles [1,2].

The dual phase (DP) steels present an excellent combination between high mechanical strength and good ductility when compared to carbon and manganese or microalloyed steels of the same class of mechanical strength. Its microstructure consists of a ferrite matrix, very soft, which provides a lower yield limit associated with a high uniform elongation, and second phase islands, formed mainly by martensite, of high hardness, which ensure the high mechanical strength to the material [1,3]. This feature makes these steels especially suitable for the automotive industry, enabling the manufacture of components with more complex geometries, but conferring mechanical strength to them. Structural parts, bumper reinforcements, internal and external door panels and automotive wheels are examples of application of dual phase steels, where weight reduction is achieved by reducing the thickness of the component [4,5].

Dual phase steels can be produced by both hot rolling and cold rolling followed by annealing [5,6]. In this work, the dual phase steel obtained in the hot rolling mill was studied, having as main variables to obtain the microstructure and mechanical properties, after the last rolling pass, the intermediary temperature (IT), the residence time at the isothermal holding time (pt) and the coiling temperature (CB) [7]. Through dilatometry techniques, the effect of these variables on the microstructure and hardness of a dual phase steel of the strength class of 800 MPa was evaluated, in order to support its production on an industrial scale.

2 MATERIALS AND METHODS

The material used in this study is a hot-rolled DP800 steel with additions of Mn, P and Cr. The range of chemical composition of its main elements is presented in Table 1.

Table 1. Chemical composition (% in weight)

C	Si	Mn	P	Al	Cr
0.07 to 0.14	≤ 0.15	1.25 to 1.65	0.030 to 0.075	0.005 to 0.080	0.40 to 0.80

From a hot rolled coil, industrially produced at Usiminas' Ipatinga plant, samples were taken for the experiments using a BÄHR DIL 805 A/D dilatometer. Flat specimens were used, with 10 mm long, 4 mm wide and with original thickness, corresponding to 2.3 mm, were drawn in the middle region of the coil width, with the length parallel to the rolling direction

To perform the dilatometric tests, the thermal cycle shown in Figure 1 was used as reference. Basically, the simulated cooling profiles were preceded by heating at 10°C/s to 880°C, followed by soaking of 30 s for homogenization of temperature and microstructure. After soaking, the specimens were cooled at 10°C/s to 830°C, representing the temperature of the last rolling pass (finishing), where they were held for 2 s.

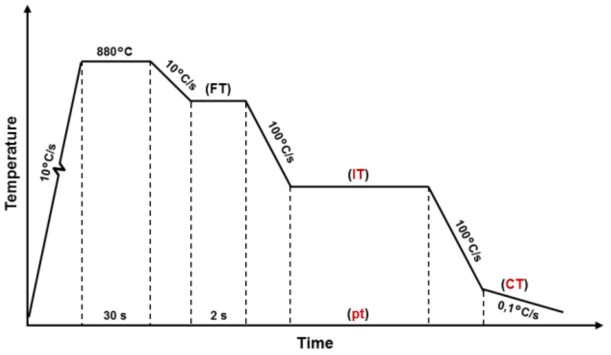


Figure 1. Schematic representation of the thermal cycle used as the basis for the simulations performed in the dilatometer.

In a preliminary analysis, the specimen was subjected to the cooling of 100°C/s, from the temperature of 830°C, to room temperature (25°C) in order to determine the intercritical field. Then, the cooling parameters were individually varied according to the following ranges:

- IT: from 620°C to 740°C, in intervals of 20°C, with pt of 60 s;
- pt: 1 s, 2 s, 3 s, 5 s e 10 s for IT = 680°C;
- CT: from 50°C to 400°C, in intervals of 50°C.

It was used cooling rates of 100°C/s, between the finishing, intermediary and coiling temperatures and of 0.1°C/s, simulating the slow cooling of the material after the coiling.

To evaluate the effect of the isothermal holding on the phase transformation of the remaining austenite, two CCTs (Continuous Cooling Transformation) diagrams [8] were elaborated. In the first one, different cooling rates were applied after soaking at 830°C for 30 s, that is, in specimens in the condition with 100% austenite. In the second, the same cooling rates were applied, however after the transformation of about 50% of the austenite into ferrite, obtained after the holding time of 10 s at the intermediary temperature of 680°C [9].

The microstructure of the specimens after the simulations was characterized by optical microscopy (OM) and scanning electron microscopy (SEM), in longitudinal section to the rolling direction. The hardness tests were carried out on a Vickers scale, with a load of 5 kgf (HV_5), in 5 positions along the middle of the specimens width, also in longitudinal section to the rolling direction.

3 RESULTS AND DISCUSSION

3.1 Effect of intermediary temperature

Figure 2 shows the dilatometric curve and the microstructure of the performed test in order to determine the intercritical field. In Figure 2 (a) three distinct phase transformation regions are observed, with start temperatures around 660°C, 520°C and 420°C. Considering the constituents present in the microstructure of Figure 2 (b), it can be stated that these regions correspond, respectively, to the formation of ferrite, bainite and martensite. It is also possible to observe that only for the intermediary temperatures of 640°C and 620°C the decomposition of the austenite began before the beginning of the isothermal holding. Applying the lever rule on the ferrite formation region in the curve of Figure 2 (a), it is possible to make an approximation of the evolution of the transformed volume fraction along the cooling, as shown in Figure 3 [10]. As the volume fraction of ferrite measured by quantitative metallography in the final microstructure was equal to 10%, the percentages of 0.5% and 1.5%, respectively were estimated for the beginning of the holding at the intermediary temperatures of 640°C and 620°C. For the higher intermediary temperatures, the ferrite volume fraction at the beginning of the holding was considered equal to zero.

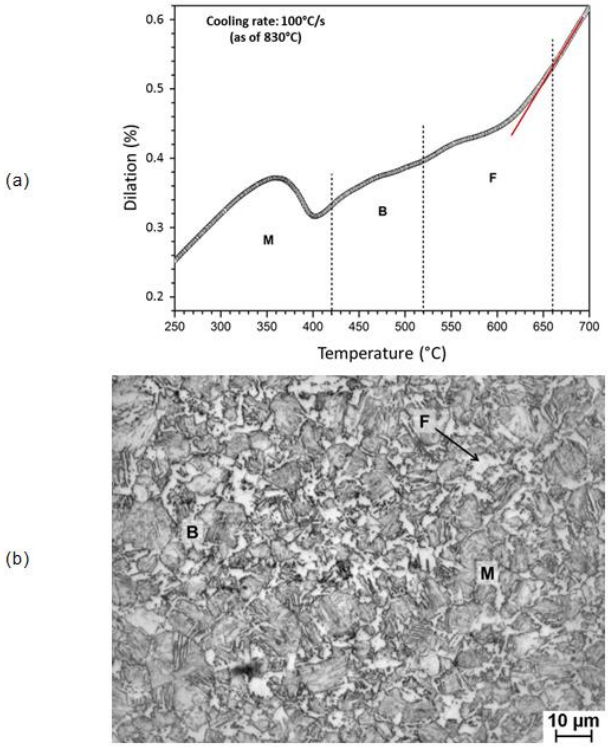


Figure 2. (a) Dilatometric curve and (b) microstructure obtained in the test to determine the intercritical field. Attack: Nital 4%. OM, 1,000X original magnification.

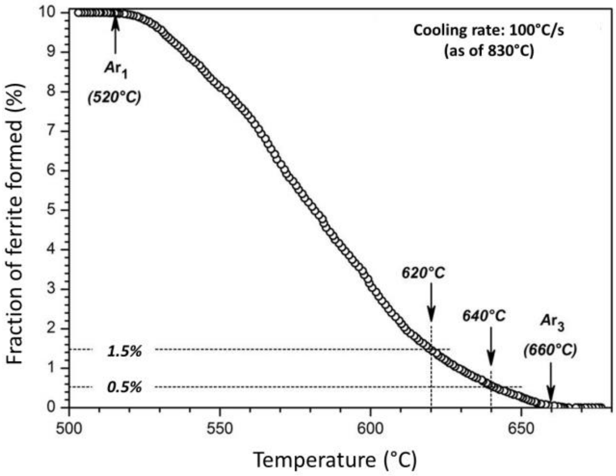


Figure 3. Fraction of ferrite formed in the test to determine the intercritical field.

The percentage variation of specimens length over time for each of the tests performed, varying only the intermediary temperature, is shown in Figure 4. In all cases, a specimen expansion is observed as the holding time increases in each temperature. As the temperature was maintained constant along the plateau, this expansion can only be associated to the formation of ferrite, which causes an increase in the parameter of the crystalline lattice and therefore in the volume of the specimen.

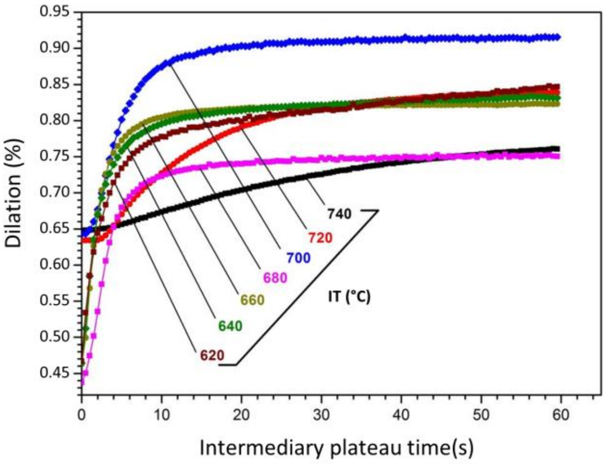


Figure 4. Specimen dilatation along the holding time at each of the isothermal levels in the TI.

Comparing the dilatometric curves shown in Figure 4, it is difficult to visualize the behavior regarding the effect of IT due to the dilation of the specimen, in relation to its initial length not being the same for all tests. This analysis can be performed by considering that the increase in specimen length is related to the transformation of austenite into ferrite and is therefore proportional to the ferrite volume fraction formed. The volume fraction of ferrite present at the beginning of the isothermal plateaus had previously been determined by the dilatometric curve of the test performed to determine the intercritical field, according to Figure 3. On the other hand, the volume fraction of ferrite at the end of the plateau was associated with the values measured by metallography quantitative analysis in the final microstructure obtained in each specimen cooled rapidly after the 60 s holding in the isothermal plateau, in order to "freeze" the transformation of phases in that condition.

Figure 5 shows the microstructures obtained at the end of the 60 s plateau for the intermediary temperatures evaluated. In all cases, the microstructure is formed by second-phase islands in a ferrite matrix with polygonal grains. As the intermediary temperature decreases an increase in the amount of ferrite and a reduction in the size of both the ferrite grains and the second-phase islands is observed.

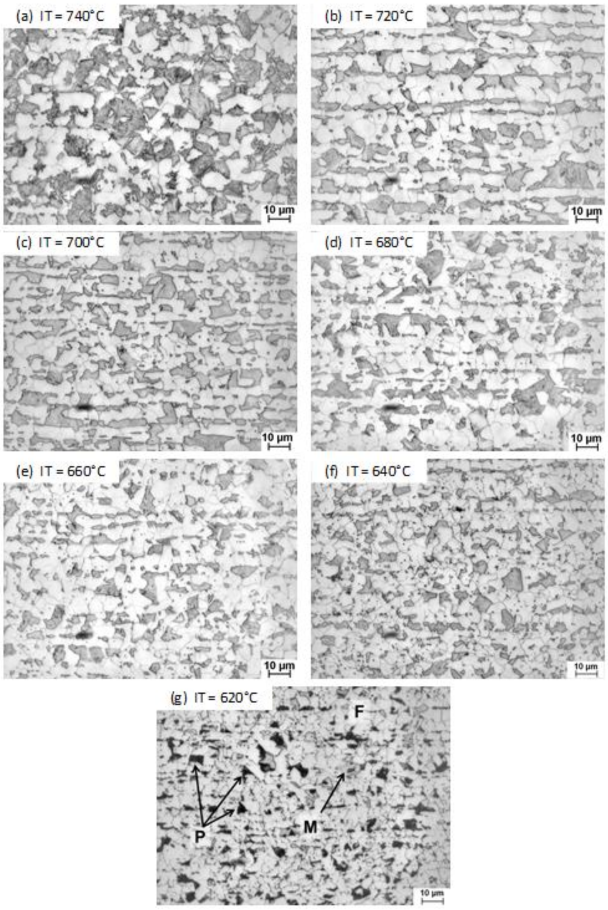
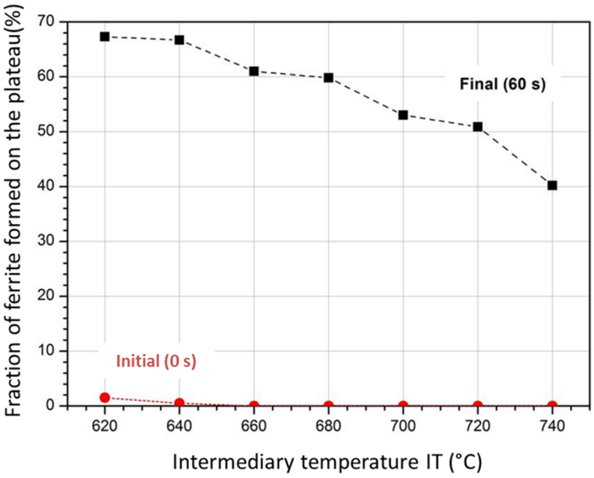


Figure 5. Typical microstructures observed at the end of 60 s levels with different ITs. Attack: Nital 4%. OM, 1,000X original magnification.

For the intermediary temperatures equal to or greater than 640°C, the second phase is predominantly martensite and only for the highest evaluated IT (740°C, Figure 5(a)) was observed the existence of some bainite-like regions in the interior of the larger islands. On the other hand, in the microstructure referring to the 620°C plateau, in addition to martensite islands a significant amount of pearlite is also observed, as indicated in Figure 5(g) [11]. Figure 6 shows the amount of ferrite present at the end of the various simulated isothermal stages and also the ferrite fraction at the beginning of each plateau, which was determined from the curve of Figure 3. According to these data, it is noticed an increase in the volume fraction of ferrite as the intermediary temperature decreases.



IT (°C)		620	640	660	680	700	720	740
Ferrite (%)	Initial (0 s)	1.5	0.5	0	0	0	0	0
	Final (60 s)	67.3	66.7	61.0	59.8	53.0	50.9	40.2

Figure 6. Quantity of ferrite present at the beginning and end of the isothermal plateau of 60 s for the ITs evaluated.

Figure 7 shows the evolution of the transformed volume fraction of the austenite along the holding time at the simulated isothermal stages, estimated from the curves of Figure 4, and initial and final ferrite fractions indicated in Figure 6. It is verified that the decrease of IT causes an acceleration of austenite decomposition, in addition to an increase in the volume fraction of ferrite formed at the end of the 60 s plateau, as already identified in Figures 5 and 6. For temperatures of 720°C and 740°C, it was observed that the transformation of the austenite is slower in comparison to the others, taking even a few seconds to start. For temperatures equal to or less than 700°C the ferrite fraction reaches an approximately constant value for decreasing times as IT decreases. In addition, it is clear that for IT of 660°C, 640°C and 620°C the transformation starts immediately at the beginning of the plateau and continues at high speed, similar to the three temperatures for about 7 s. Particularly for the IT of 620°C it is observed a change of inclination near to the middle of the isothermal plateau (time of 33 s), which was not observed for the other temperatures. As mentioned previously, the microstructure obtained at the end of the 620°C plateau (Figure 5 g) had a significant amount of pearlite. In this way, it can be concluded that the acceleration in the expansion of the specimen from the middle of the 620°C plateau is associated with the final formation of the ferrite and the beginning of the pearlite, as indicated in Figure 7.

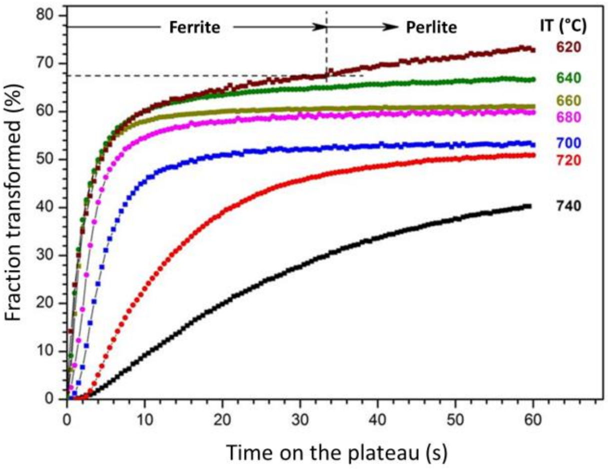


Figure 7. Transformed fraction of austenite at the isothermal levels of dilatometric curves.

Figure 8 shows the dilatometric curves obtained in the fast cooling applied at the end of the isothermal plateaus of 60 s. It is observed that the phase transformation initiated at the plateau continued to advance at the beginning of the cooling, only ending between 550°C and 600°C, depending on the value of the IT. From this finding it can be assumed that the volume fraction of ferrite formed only during the holding time at the isothermal plateau should be smaller than that measured in the final microstructure, which also includes the portion formed in the fast cooling [12]. However, as it was not possible to determine this portion, the amount of ferrite in the final microstructure was considered as a rough estimate of the fraction formed along the isothermal plateau.

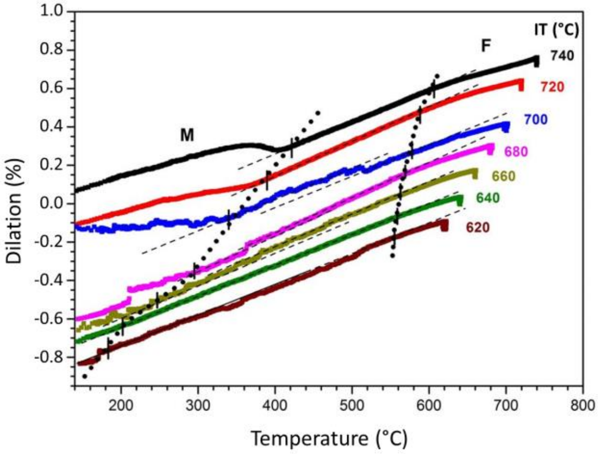


Figure 8. Dilatometric curves obtained in the fast cooling (100°C/s) applied after the isothermal plateau in the ITs evaluated.

Another interesting aspect that can be observed in the dilatometric curves of Figure 8 is the reduction of the martensite volume formation temperature (Ms) as IT decreases, which is associated to the amount of ferrite formed, both in the isothermal plateau and in subsequent rapid cooling [11]. That is, the higher the ferrite volume fraction formed, the smaller the amount of austenite remaining, and therefore the higher the C content, since the solubility of this element in the ferrite is very limited. The increase of the C content in the austenite, in turn, hinders the formation of martensite and caused a decrease of the order of 200°C in Ms, from about 400°C to below 200°C, respectively, between the highest (740°C) and lowest (620°C) ITs evaluated.

The hardness results showed a good correlation with the phase volume fractions observed in the microstructures of Figure 5, as shown in Table 2. It is observed that the higher the percentage of second phase the higher the hardness values. However, even with a small variation of the fraction of phases observed for the ITs of 620°C and 640°C, a greater reduction in the hardness value for the IT of 620°C is observed. This result is in line with the presence of pearlite in the microstructure relative to this lower IT, as discussed previously (Figures 5(g) and 7).

Table 2. Phase volume fractions and hardness results of tests performed with IT variation

IT (°C)	Ferrite (%)	Second phase(%)	Hardness (HV_{5kgf})
620	67.3	32.7	168
640	66.7	33.3	189
660	61.0	39.0	193
680	59.8	40.2	200
700	53.0	47.0	210
720	50.9	49.1	221
740	40.2	59.8	239

3.2 Effect of the holding time on the isothermal plateau

Figure 9 shows the microstructures obtained in the tests with variation of the holding time in the isothermal plateau at 680°C. It is observed that with increasing time the ferrite volume fraction also increases and the second-phase islands, formed from the remaining carbon-enriched austenite, are more isolated and distributed in the ferritic matrix [11].

Phase fractions and hardness results are presented in Table 3. A reduction in hardness values is observed with increasing ferrite ratio and reduction of the amount of second phase. This suggests that the increased hardness of the second phase, formed from the carbon-rich remaining austenite, was not enough to compensate for the softening resulting from the increase in the ferrite volume fraction, justifying this behavior.

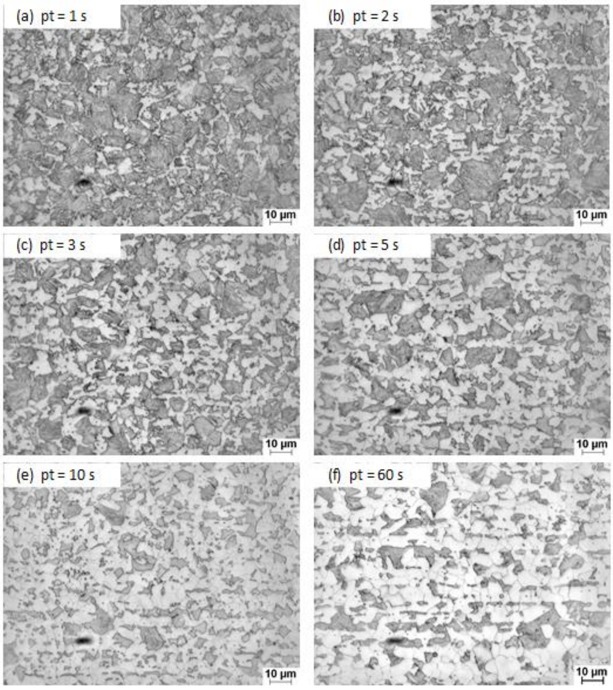
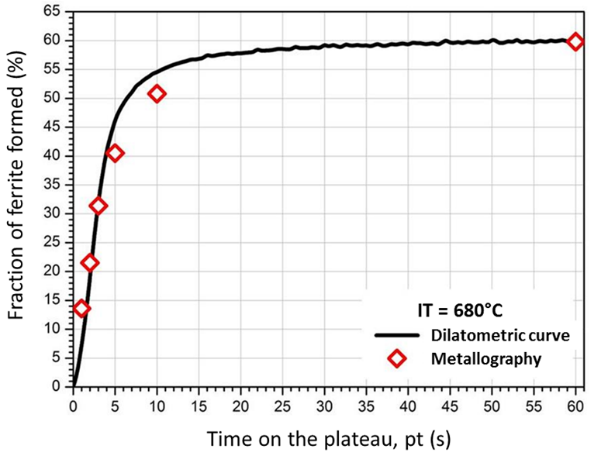


Figure 9. Microstructures obtained in the tests with variation of the holding time in the isothermal plateau of 680°C. Attack: Nital 4%. OM, 1,000X original magnification.

Table 3. Phase volume fractions and hardness results of the tests performed with variation of the holding time at the isothermal plateau of 680°C

Time (s)	Ferrite (%)	Second phase(%)	Hardness (HV_{5kgf})
1	13.6	86.4	281
2	21.5	78.5	278
3	31.4	68.6	250
5	40.5	59.5	234
10	50.8	49.2	219
60	59.8	40.2	200

Another important observation is the comparison between the amount of ferrite shown in Table 3 and the values estimated by the application of the lever rule on the dilatometric curve relative to the 60 s plateau at 680°C IT, indicated in Figure 7. Note a good cohesion between the results, since the actual values were close to the estimated ones, as can be observed in Figure 10.



ps (s)	0	1	2	3	5	10	60
Ferrite (%)	0	13.6	21.5	31.4	40.5	50.8	59.8

Figure 10. Estimated and actual values of the transformed volume fraction of ferrite during the residence time at the isothermal plateau of 680°C.

3.3 Effect of coiling temperature

The dilatometric curves obtained in the tests performed with variation of CT are presented in Figure 11. By analyzing these curves it was possible to observe that the final temperature of transformation of austenite in ferrite (Ar_1) is around 540°C. Below that temperature, CT curves of 250°C or less show a small deviation, which continues to about 280°C, where a more marked deviation occurs, representing the martensite formation start temperature (Ms). In CT curves above 250°C, the deviation between temperatures Ar_1 and Ms is more evident, indicating a significant bainite formation, as it will be seen in the microstructural analysis below. In all curves, the abrupt reduction of the cooling rate (from 100°C/s to 0.1°C/s) at the point corresponding to CT was followed by a significant expansion of specimen, especially for the highest CT (400°C, 350°C and 300°C).

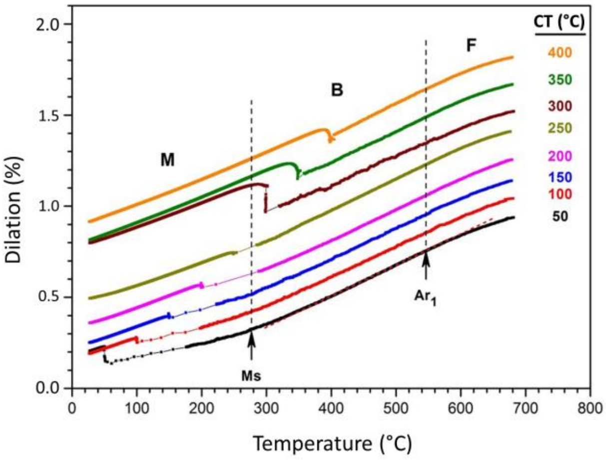


Figure 11. Dilatometric curves obtained with cooling with different coiling temperatures.

The microstructure obtained in the tests with variation of CT are presented in Figure 12. In all cases, as expected, there are no changes in the amount and morphology of the ferrite. The mean volume fraction of ferrite measured in the optical microscope was 54%, ranging from 52% to 56%. On the other hand, in relation to the second phase, although the quantity remains practically constant, its aspect changes with the CT alteration, mainly for CTs higher than 250°C, for which a gradual replacement of the second martensite phase with bainite is observed [6].

The hardness results were aligned with the changes observed in the dilatometric curves and with the microstructure obtained. According to Figure 13, the average hardness shows a tendency to fall continuously as CT increases, being slower until CT equal to 250°C and more pronounced for CTs above this value. In micrographs below 300°C, predominance of martensite was observed in the second phase islands, whereas for the higher coiling temperatures, even for CT equal to 300°C, this constituent was gradually replaced by bainite. It is emphasized that the larger the CT within the martensitic field, the greater the possibility of self-tempering of the martensite formed, whose hardness tends to fall [13].

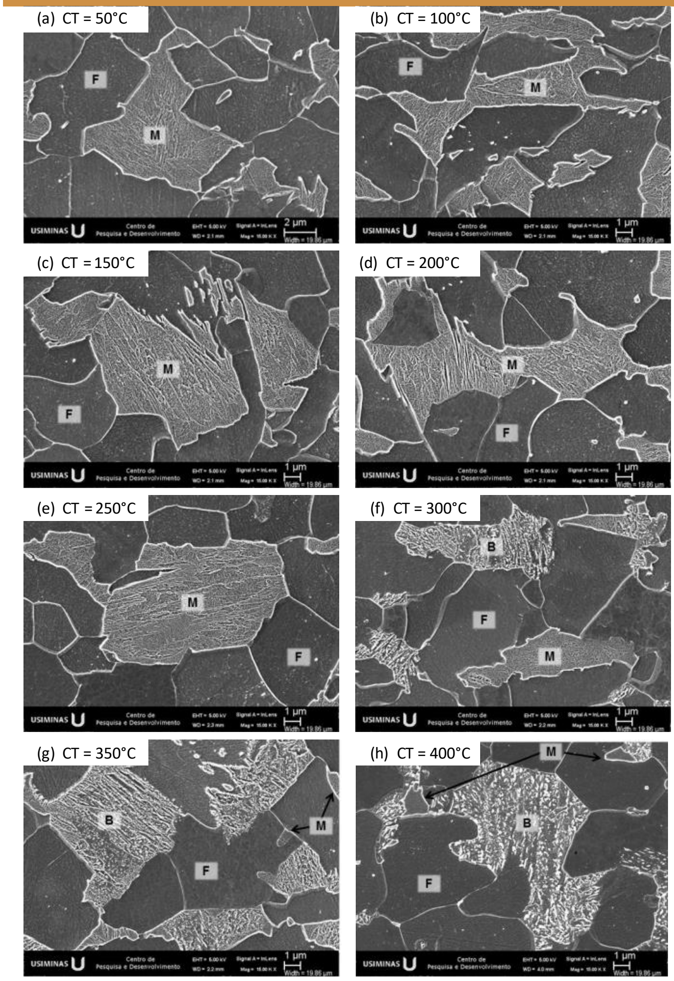


Figure 12. Typical microstructures obtained in the cooling with different CTs. Attack: Nital 4%. SEM, original magnification 15,000X.

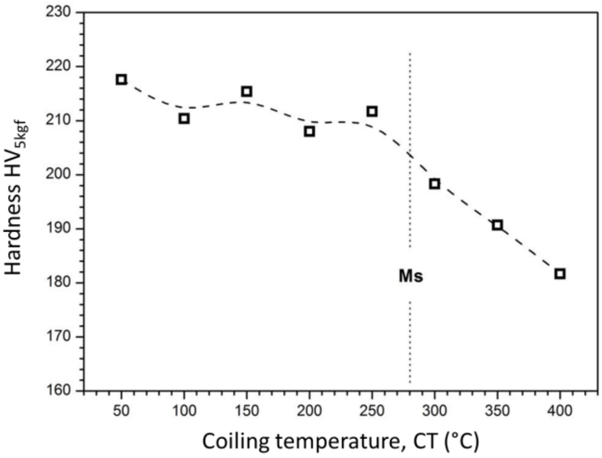
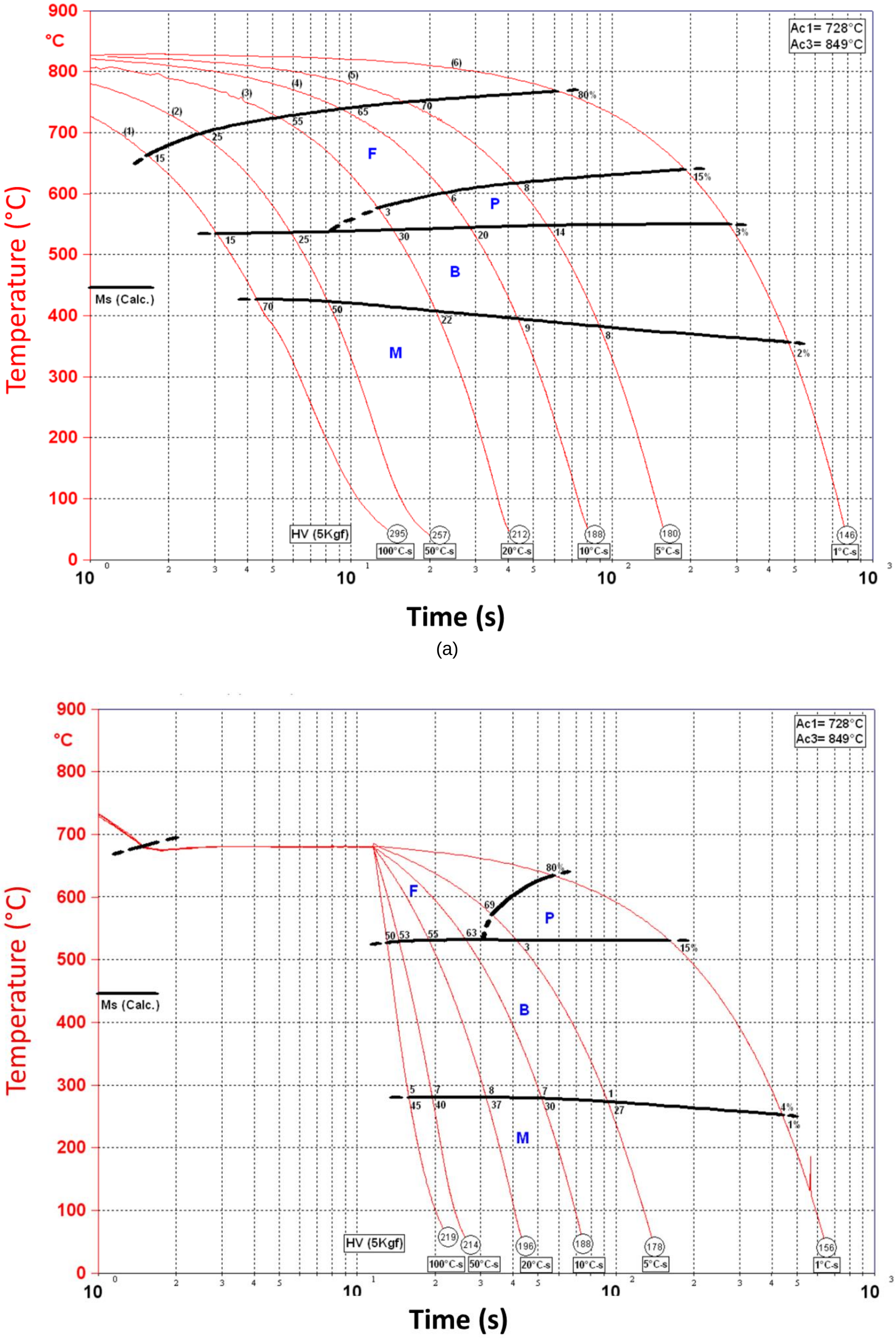


Figure 13. Average hardness obtained in the specimens submitted to the cooling with different coiling temperatures.

3.4 CCTs diagrams

The CCT diagram of the steel evaluated in the fully austenitic condition, that is, with the cooling applied soon after the 2 s soak at 880°C, is shown in Figure 14(a). The formation of ferrite, bainite and martensite is observed for all the cooling rates between 1°C/s and 100°C/s. As shown in Figure 14(b), these same constituents were formed when the quenching was applied after the 10 s step at 680°C, i.e., with about 50% remaining austenite.

The main difference between the two diagrams is in the martensite field. The formation of about 50% ferrite during the isothermal step, with the consequent increase in the amount of carbon in the remaining austenite, caused a reduction of more than 100°C at the Ms temperature. In addition, it is found that the enrichment of the austenite also caused a delay in the formation of pearlite. These results confirm the important effect of the intermediary level on obtaining the biphasic microstructure aimed at the steel evaluated after hot rolling and coiling.



(a)

(b)

Figure 14. CCT diagrams for steel with (a) 100% and (b) about 50% austenite.

4 CONCLUSIONS

The obtained results showed that the temperature of the intermediary plateau (IT) has a strong influence on the kinetic of the phase changes. The lower the IT, the higher the rate of ferrite formation and the lower the amount of austenite remaining at the end of the plateau. This lower amount of austenite is enriched with carbon during the residence time at the isothermal plateau, which avoids the formation of pearlite and bainite during the final cooling. However, for very low IT values, the risk of pearlite formation is still high, as observed for the 620°C IT.

The residence time at the isothermal plateau (pt) has a strong influence on the amount of ferrite formed and, consequently, on the final microstructure and hardness of the material. The rate of ferrite formation is significantly higher at the beginning and decreases along the plateau.

The variation of the coiling temperature (CT) did not cause a significant change in the amount and morphology of the ferrite. On the other hand, for CTs above 250°C a gradual substitution of martensite for bainite was observed, which, in addition to the effect of self-tempering to higher CTs, contributed to the hardness reduction.

It was verified that the holding of 10 s in the intermediary plateau at 680°C resulted in the enrichment of C of the remaining austenite, contributing to the formation of the biphasic microstructure aimed at the steel evaluated.

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