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Analysis of the influence of the composition and quenching parameters on the performance of some dual phase in HSLA steels

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ABSTRACT

Due to its combination of high mechanical properties, good formability, and low production cost, steel is a key material with potential for improvement in the metallurgical industry. Based on these conditions, this research evaluated the influence of material composition and incomplete austenitization parameters on the final metallurgical and mechanical properties of high-strength microalloyed steels after cooling in a medium with high severity. The applied cycle was based on the intercritical thermal treatment of microalloyed steels with niobium (Nb) and titanium (Ti) to increase the mechanical resistance and guarantee the tenacity of the material. An experimental study was carried out testing three intercritical temperatures, 806 °C, 775 °C, and 740 °C, with subsequent cooling in polymeric solutions in water. The studies showed that the intercritical temperature variation directly contributed to the difference in the second phase microstructure present in the samples. The heat treatment findings resulted in a microhardness of 434.2 HV0.01, characterizing the low-carbon martensite. The presence of a matrix consisting of ferrite and a second phase of low-carbon martensite promoted the typical behavior of dual phase steel. In the x ray diffraction, the presence of retained austenite was not evidenced, indicating the efficiency of the cooling rate. The experiments confirmed the influence of different engineering parameters and intercritical treatment on the mechanical properties. The study enriches the current knowledge about the development of variables for the development of dual phase steel from microalloying elements.

Keywords: Intercritical Quenching; HSLA Steels; Dual Phase Steel.

1. INTRODUCTION

In Brazil, the automobile industry is one of those that most generates income, jobs, and investments in the national economy. In order to improve the efficiency and sustainability of engines, the Brazilian government created the ROTA 2030 program in 2018 [1].

ROTA 2030 defines the rules for manufacturing and distributing vehicles in Brazil. This program aims to generate benefits for innovative companies that invest in new technologies and promote safety, efficiency, and protection of the environment. In this context, materials can make an important contribution [1, 2]. Heat treatment is a process that involves heating and cooling steels to alter their microstructures and mechanical and metallurgical properties [3, 4]. During the heating and cooling cycles, the microstructure of the materials presents phase changes by diffusional or non-diffusional processes [5]. In low-carbon steels, martensite with a lath-like morphology is known to form during quenching of low to medium carbon steels after austenitizing and quenching in high-severity media [6]. The crystalline structure of martensite in laths is body-centered tetragonal and can overlap body-centered cubic peaks in X-ray diffraction (XRD) tests [6, 7].

However, little is known about the substructural evolution of laths in tempered low-carbon microalloyed martensitic steels [6]. Martensitic transformations follow a displacement mechanism that invariably results in the generation of transformation-induced plasticity. This introduces dislocations and can promote twinning within the matrix, depending on the steel composition [6]. In microalloyed steels with low carbon, the martensite

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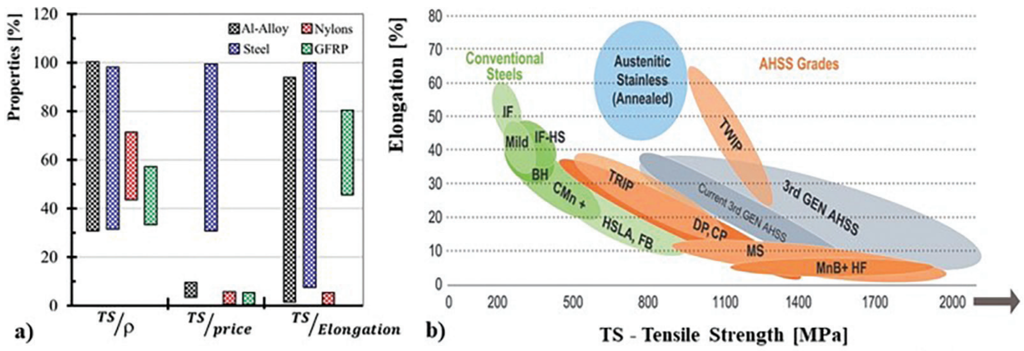

Figure 1: Comparison of mechanical properties for different materials (a) and different generations of steel developed in recent decades (b).

is preferably nucleated close to the grain boundaries, presenting a smaller volume in relation to the ferritic matrix [7–9]. While the ferritic matrix confers ductility to the material, mechanical strength is favored by the second martensitic phase.

Dual-phase steels have proven scientific relevance in materials science and industrial applications, mainly in the automotive, oil, and naval industries, due to their ability to reduce vehicle weight and fuel consumption. Two-phase steels are classified as advanced high-strength steels (AHSS) [1–5]. In this sense, another essential technology in materials science refers to microalloyed steels. In microalloyed steels, alloying elements are added in small amounts, generally less than 1% by weight [6, 7]. They are fundamental for the precipitation of carbides and are of great importance as the parameters used in thermomechanical processing. The chemical elements interfere in the grain size growth of the austenitic material and in the distribution of these carbides, which directly influence the mechanical strength and toughness of the steel [7, 8]. Microalloyed steels have attracted increasing industrial interest in applications such as oil and gas pipelines, marine equipment, and the automotive industry due to their superior performance and mechanical properties [4,5]. Research on the behavior of microalloyed steels with two-phase microstructure represents a relevant technological factor in antagonistic mechanical properties [6–9]. The two-phase microstructure in microalloyed steels is obtained through intercritical treatment. In this heat treatment, the temperature of the steel reaches the intercritical region, which comprises the area between AC1 and AC3 of the iron-carbon diagram [7, 9]. In this region, the ferritic and austenitic phases coexist, and the subsequent rapid and continuous cooling ensures the adiffusional transformation of austenite into a martensite microstructure. This process originates from the low carbon ferrite and martensite phases of steel [10–11].

In addition to the advantages of light weight materials, the major challenge is associated with their higher cost. In this sense, steel still remains a critical material with great economic potential in the automotive industry [5, 7]. Our study provides scientific contributions to advance the understanding of how to obtain two-phase steel from HSLA steels (microalloyed with Nb and Ti) to increase its mechanical strength. Another gap addressed in this research refers to the comparison of the behavior between the two-phase steel microalloyed with Nb and Ti and the conventional materials found in the existing literature [11–14]. Figure 1 shows different generations of steel and their mechanical properties.

By combining chemical composition and manufacturing process, steel can achieve a wide range of properties and ratings (Dual Phase Steel, HSLA, Interstitium Free). Generally, HSLA steels contain low carbon content, a relevant factor for their toughness, weldability, and formability. Microalloying elements are capable of anchoring the growth of austenitic and ferritic grains through the formation of carbides and nitrides that are added to their chemical composition. The main microalloying elements are V, Nb, or Ti. Aluminum has a great influence on this class of steels because, together with nitrogen, it acts in the precipitation hardening mechanisms.

HSLA steels require thermal cycling to optimize their mechanical properties. On the other hand, biphasic steels are low carbon steels that have other mechanisms for obtaining mechanical properties, and their main microstructures are mainly composed of ferrite and Martensite phases. Ferrite is responsible for toughness, and martensite islands provide mechanical resistance [13, 14].

There are several routes for the production of DP steel. One involves rapid cooling of the intercritical (A3 < IT < A1) to room temperature. Rapid cooling ensures the diffusion-free Transformation of austenite into martensite, resulting in a mixed microstructure. These particular transformation temperatures are determined by the composition of the steel and the carbon content. The chemical composition determines the thermodynamic

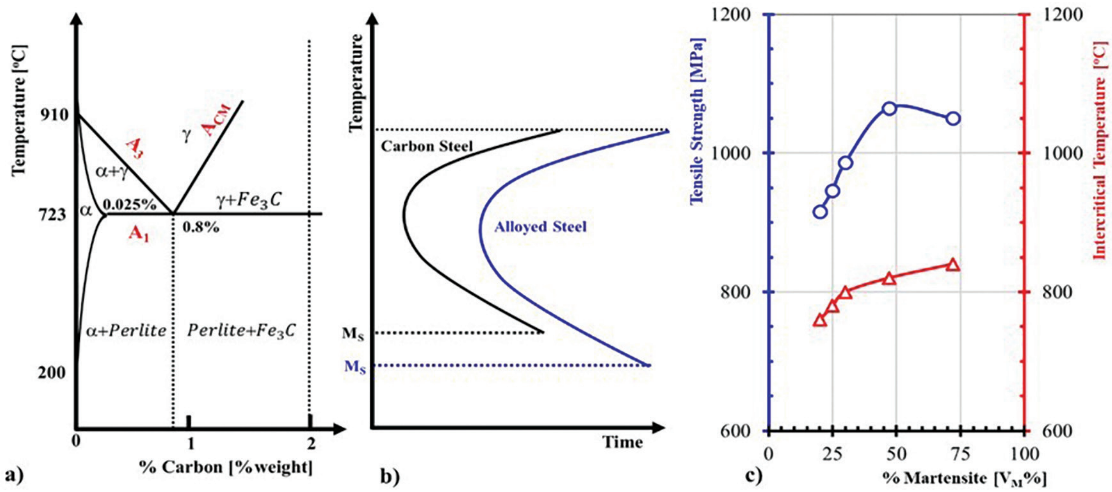

Figura 2: Fe-C diagrams in a), TTT in b), and correction of martensite volume, intercritical temperature, and mechanical strength in c).

parameters of the materials and the transformation behavior of austenite, which therefore influences the wetting and cooling behavior during quenching. The carbon equivalent (CE) determines the hardenability of the steel, where the concentration of each Solute is scaled by a coefficient that expresses its ability to delay the austenite-ferrite transformation.

Quenching (or cooling medium) has a direct influence on heat extraction for martensite transformation (e.g., heat extraction from water > polymer solution > oil).

As a consequence, the adequate selection of the cooling medium will directly influence the transformation of the martensite and the properties of the final materials [10].

Our previous research [15–17] demonstrates the benefits of applying polymeric solutions in the Heat treatment of low alloy steels. Through the tempering of AISI 4140 steel samples in different cooling media (water, oil, and polyalkylene glycol (PAG) solution), the results demonstrate the advantages of applying PAG, which ensures better homogenization in the distribution of martensite and maintains the hardness profile by eliminating phase steam, and evolution to boiling and convection. In addition, polymeric solutions have the advantage of being biodegradable and producing a more homogeneous heat exchange throughout the quenching process [7, 8, 16, 17].

Figure 2 presents some characteristics of the transformations of the Heat treatment of Steel [8]. Figure 2a shows a fraction of the Iron – Carbon equilibrium diagram, which indicates the transformation temperatures (A3, A1, and ACM). Figure 2b shows a typical representation of a Time-Temperature-Transformation Diagram. Note that the presence of alloying elements can shift the MS (Start of Martensite Transformation) curves in the right direction, increasing the hardenability of the materials [11]. Figure 2c shows the relationships between martensite content and intercritical temperature on the tensile strength of an HSLA [7, 8, 18].

Literature reports that the increase in martensite fraction in DP steels promotes crack initiation and thus results in worse ductility. Therefore, the martensite fraction should be kept in the range of 10–40% [17–21].

2. MATERIALS AND METHODS

2.1. Obtaining intercritical temperatures

This research aimed to obtain a two-phase steel from a Nb and Ti microalloyed steel capable of increasing the mechanical resistance, guaranteeing the toughness of the steel. We examined the results at three temperature levels: 806 °C, 775 °C, and 740 °C, and subsequently the samples were cooled in an aqueous solution with 10% polymer. Three compositions of HSLA steels were analyzed in this research (Table 1). The samples had a carbon content between 0.13 and 0.15% to maintain formability and manganese between 1.04 and 1,43%. Other alloy elements that influenced the hardenability found were Chromium (Cr), Nickel (Ni), and copper (Cu) as residual processing elements, with the presence of Niobium (Nb) and Titanium (Ti) as microalloying elements [7, 8, 18].

The intercritical temperatures were calculated using the Andrews Equation [16, 17]. Equations 1 and 2 were used to calculate the temperatures of lines (A3) and (A1) relative to the intercritical zone. Equation 3

Table 1: HSLA chemical composition (% weight).

HSLA	%C	%Si	%Mn	%Cr	%Ni	%Cu	%Nb	%Ti
A	0.150	0.317	1.33	0.0213	0.0126	0.0149	0.029	0.0170
B	0.140	0.276	1.43	0.0102	0.0099	0.0130	0.0328	0.0151
C	0.130	0.316	1.04	0.0277	0.0136	0.0122	0.0236	0.0045

calculated the initial temperature for the martensitic transformation (MS) to be considered in the severe cooling process to obtain low carbon martensite [7, 8, 22].

$$A_3 = 910 - 203\sqrt{C} - 15.2Ni + 44.7Si + 104V + 31.5Mo + 13.1W \\ - 30Mn + 11Cr + 20Cu - 700P - 400Al - 120As - 400Ti \tag{1}$$

$$A_1 = 723 - 10.07Mn - 16.9Ni + 29.1Si + 16.9Cr + 290As + 6.38W \tag{2}$$

$$M_S = 539 - 423C - 30.4Mn - 17.7Ni - 12.1Cr - 7.5Mo \tag{3}$$

The Carbon Equivalent content (CE) was calculated through Equation 4 [26].

$$CE = C + \frac{Mn + Si}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \tag{4}$$

2.2. Heat treatment processes

In order to evaluate the manufacturing influence on material microstructure and performance, the samples were divided in to small cylinders (20 mm in length and diameter). The materials were austenitized at 850 °C for 60 minutes in a resistive oven for EDG. The HSLA samples were intercritically quenched for the following evaluations:

1st) Evaluation of the influence of the cooling media on the final microstructure of the materials (with low air cooling rates).

2nd) Evaluation of the influence of the concentration of the PAG solution (10, 15 and 20% PAG in water solution) on materials finals microstructure. During this process, a recirculation pump was continuously agitated with an outlet speed of 0.7 m/s.

3rd) Evaluation of the influence of the composition and the intercritical temperature on materials finals microstructure and properties.

After austenitization, the samples temperatures were decreased until the intercritical values, sustained for 40 minutes and cooled in the proper media. Intercritical temperature was fixed in 775 °C in the first two stages. In stage three, the intercritical temperatures variates in three levels: 740, 775 and 806 °C.

Chemical analysis was performed by optical emission spectroscopy. Three points per sample were analysed in a Foundry-Master equipment, from Oxford Instruments.

2.3. Microstructure analysis after thermal cycles

The specimens were submitted to the proper metallographic preparation for microstructural analysis and hardness evaluation. The samples were ground on abrasive papers (from 100 to 1200 mesh) and polished on a water diamond suspension (25 µm). The chemical etching was carried out with Nital 3% solution, for 40 seconds. The samples were also immersed in Klemm I (water solution saturated with $Na_2S_2O_3$ + $K_2S_2O_5$), for special microstructural analysis (Klemm I differentiates retained austenite from ferrite and martensite by tons of blue colors), where the contrast variations are associated with surface tension between the material and Klemm I [27, 28]. Microstructural analysis was performed on an optical microscope (GX 51S, from Olympus) and a Scanning Electron Microscope (SEM) (JSM-6610LV, from JEOL).

The content of martensite generated after the intercritical treatment was determined through image analysis according to ASTM E1245-16 [18–21].

Microhardness evaluations were executed at a Shimadzu tester, model HV2, following ASTM E384-22 [29]. A Vickers penetrator with a 0.01 kg load was applied for 10 seconds at each of the ten measurement points per sample.

2.4. Statistical design and analysis

The collected data were analysed through ANOVA[1] (Analysis of Variance) with 5% level of significance. The test statistic of ANOVA is the F-statistic. In this research, the ANOVA results were presented as F' (Equation 5) [23–25].

$$F' = \frac{F_{calculated}}{F_{critical}} \tag{5}$$

(if F' > 1, the parameters has significance on the data).

For this porpoise, the tests were designed as factorial experiments [22].

Three types of HSLA steels (A, B, C) were analysed in this research. The cylinders' samples were heat treated and submitted to different test analysis. All the measurements were executed in triplicate.

In the first round, the HSLA – A samples were submitted to quenching heat treatment, from fixed 775 ºC intercritical temperature, with the variation of the cooling medium (Water (W), Oil (O) and 10% PAG (P). The martensite content was utilized as performance indicator. Results present the average values of five measurements per samples. The standard deviation was below 5% (SD < 5%).

In the second round, the HSLA – A samples were submitted to quenching heat treatment, from fixed 775 ºC intercritical temperature, with the variation of the concentration of the PAG in solution (10, 15 and 20%). The martensite content was utilized as performance indicator in these stages. Results present the average values of five measurements per samples; SD < 5%.

In the third round, the HSLA steels (A, B, C) were submitted to quenching heat treatment, on a fixed 10% PAG solution cooling medium, from three intercritical temperatures (740, 775 and 806 ºC). Data were analysed through two-way ANOVA.

Martensite content and phase microhardness were utilized as performance indicators. Results present the average values of five measurements per samples (martensite content) and ten measurements per samples (microhardness); SD < 5%.

2.5. Mechanical properties and X Ray Diffraction (XDR) of samples

In the final round, the previous HSLA – A samples, which were submitted to quenching heat treatment, on a fixed 10% PAG solution cooling medium at three intercritical temperatures, were analyzed through tensile testing and XRD (only for qualitative comparison). The data were analyzed through a one-way ANOVA. Yield strength, tensile strength, elongation, and the (calculated) relative toughness were utilized as performance indicators. Results present the average values of three measurements per sample (SD < 10%).

Tensile tests were carried out using ASTM A 370-21 [30] on Shimadzu EHF-EV 200K equipment. Three samples per group were analyzed at this stage.

Finally, X-ray diffraction analysis was performed in a Bruker diffractometer, model D8 Advance, using a copper tube with a 0.15406 nm wavelength. The Bragg angle (2θ) rangevariess from 30º to 120º, with a 0.02° pitch. Data analysis was executed in the Diffrac EVA software [21].

3. RESULTS

3.1. Phases and microhardness found before and after application of thermal cycles

The calculated values for ce, a3, a1 and ms are presented in Table 2, which also presents the measured values for microhardness in each phase of the base materials (before heat treatment).

Figure 3 present the microstructural evaluation of the non-treated HSLA steel (A, B, C) analysed on this Research. The microstructures were formatted for a ferrite matrix with some perlite islands.

Table 2: HSLA properties (CE, intercritical temperatures and microhardness).

HSLA	%CE	TEMPERATURE [°C] A3 A1 MS			HARDNESS [HV0,001] FERRITE PERLITE	
A	0.433	827	719	434	194	274
B	0.429	828	717	436	211	283
C	0.364	845	722	452	192	329

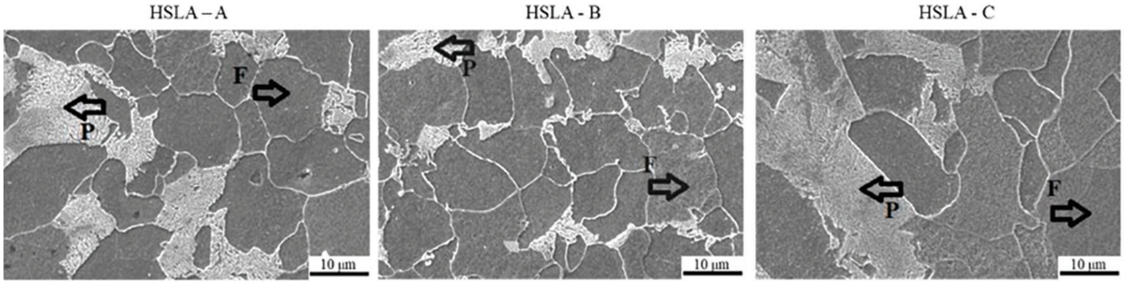

Figura 3: SEM analysis of the HSLA samples (prior to intercritical treatments).

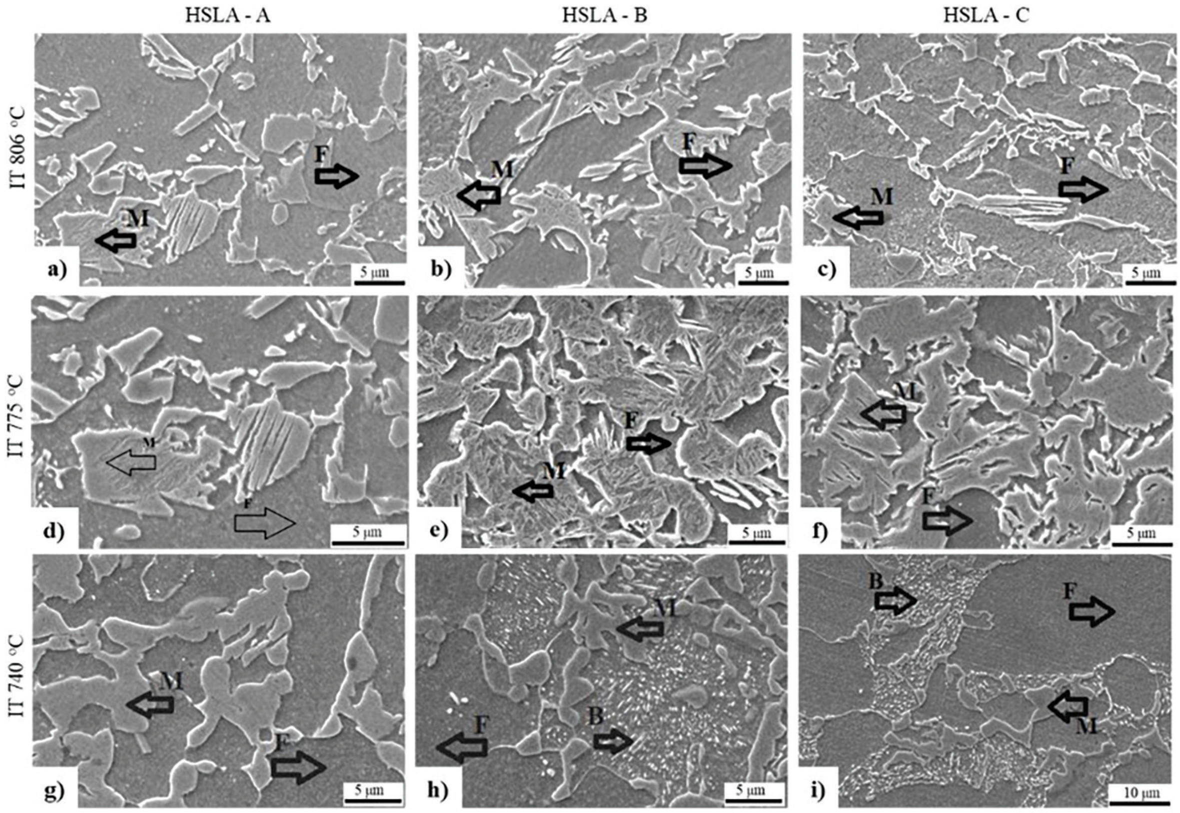

Figura 4: SEM micrographics of HSLA intercritical quenched steels.

Figure 4 presents the microstructures of the HSLA Steels after quenched on 10% PAG solution, with different intercritical temperatures. Figure 4a relates to HSLA – A quenched at 806 °C off intercritical temperature (A; 806 °C). Figure 4b (B; 806 °C), Figure 4c (C; 806 °C), Figure 4d (A; 775 °C), Figure 4e (B; 775 °C), Figure 4f (C; 775 °C), Figure 4g (A; 740 °C), Figure 4h (B; 740 °C), Figure 4i (C; 740 °C). All the microstructures present a dual phase distribution, formed for a ferrite matrix with some islands of martensite. Samples B and C, presents a fraction of bainite, after quenched from a 740 °C intercritical temperature.

The presence of bainite is related to the combination of 1.43% Mn and a low intercritical temperature. Also, the lower turbulence generated during the quenching on PAG solution (from 740 °C of intercritical temperature) decrease the cooling rate, and promote the formation of Bainite [15–18].

Figure 5 present the microstructural analysis of HSLA – A, after Klemm I attack.

The Klemm reagent acts by differentiating the phases in the HSLA microstructure through color contrast after application of the proposed thermal cycle. The ferrite phase appears as light blue, martensite as dark blue, and metallic precipitates appear at the grain boundaries.

3.2. Statistical design and analysis

Figure 6 presents the average comparison of the martensite content obtained in the first three rounds of experiments. It was observed that, in Figure 6a, F'(F' > 1) indicates that the variation in the cooling medium had an

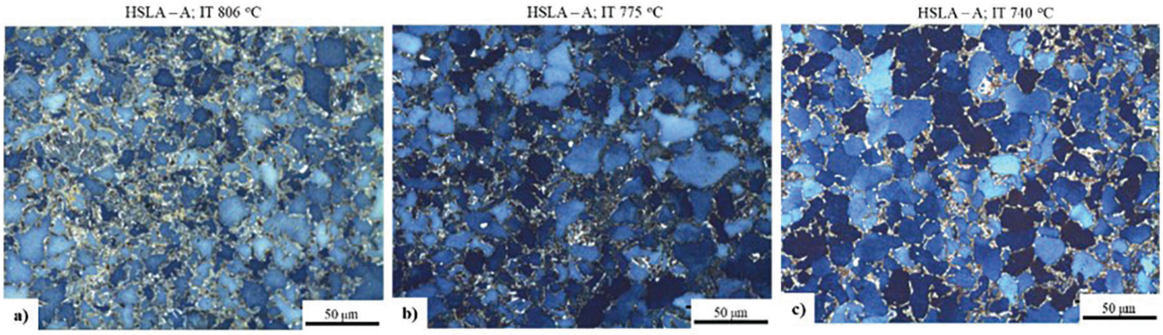

Figura 5: Microstructure of HSLA – A quenched steel, after Klemm I attack.

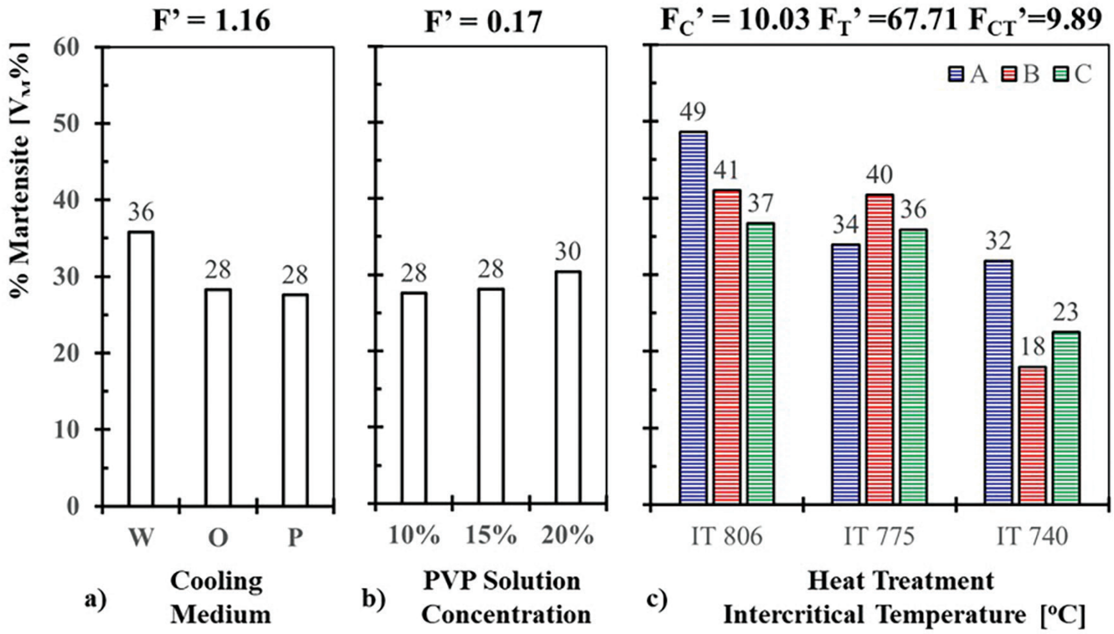

Figura 6: Martensite fraction derivate from intercritical heat treatment of HSLA samples (Dual Phase Steel).

influence on the formation of martensite when comparing water, oil and polymers. It is noteworthy that the concentrations of polymeric solutions were similar to those of conventional and accelerated tempering oils. The increase in PAG concentration in the aqueous solution from 10% to 15% and 20% was not significant (Figure 6b; F' < 1). In Figure 6c, the FC' indicates the variance ratio related to the variation in the chemical composition of the materials, the FT' indicates the variance ratio related to the intercritical temperature variation, and the FCT' indicates the variance ratio related to the interaction of both variables. All results demonstrate the strong influence of chemical composition and intercritical temperature on the formation of martensite content, after quenching in a 10% PAG solution.

Note that, in addition to having a low carbon content, the presence of Mn, Nb and Ti, as alloying elements, ensures an increase in the formation of martensite for the HSLA-B samples, tempered from 775 °C (Figure 5c).

3.3. Mechanical properties and X Ray Diffraction (XDR) of samples

Figure 7 presents the results from HSLA–A, before and after the heat treatments. F' relates to the influence of the intercritical temperature variation on the mechanical properties of the dual phase steel. The yield strength (FYS') had the highest significance. In the fracture after application of mechanical tests, coalesced microhalves typical of ductile fracture were detected at all intercritical heating temperatures and cooling rates.

Figure 8 present the X-ray diffractograms from HSLA – A samples before and after the intercritical heat treatment. Figure 8a present the result from base material. Figure 8b present the result from HSLA – A, quenched at 740 °C. Figure 8c present the result from HSLA – A, quenched at 775 °C. Figure 8d present the result from HSLA – A, quenched at 806 °C.

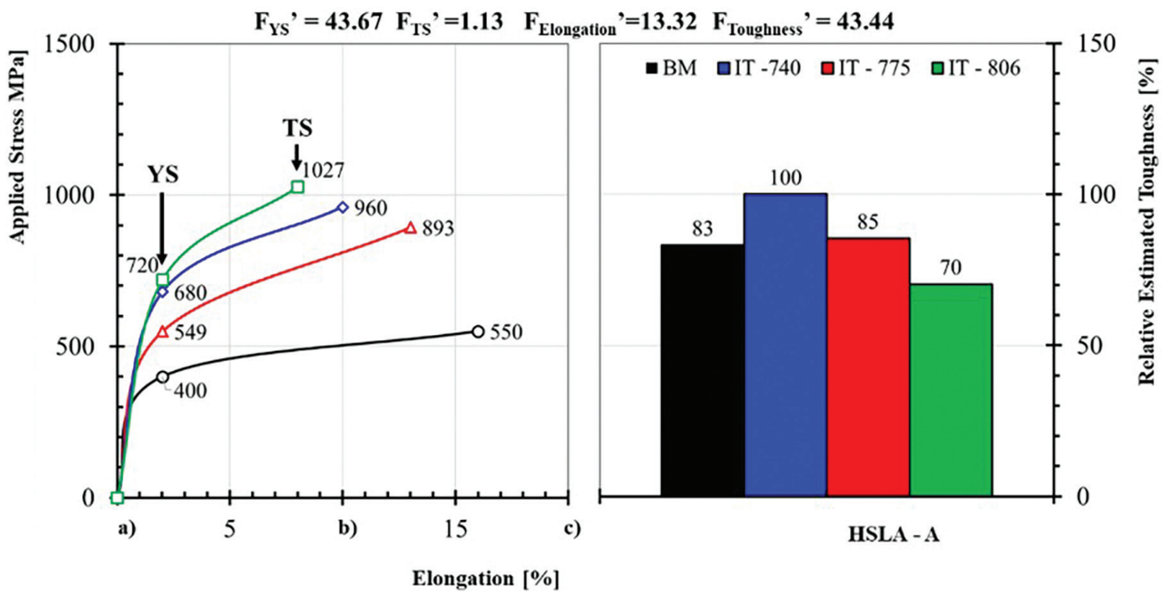

Figura 7: Mechanical properties of HSLA – A steels, prior and after quenched at three intercritical temperatures.

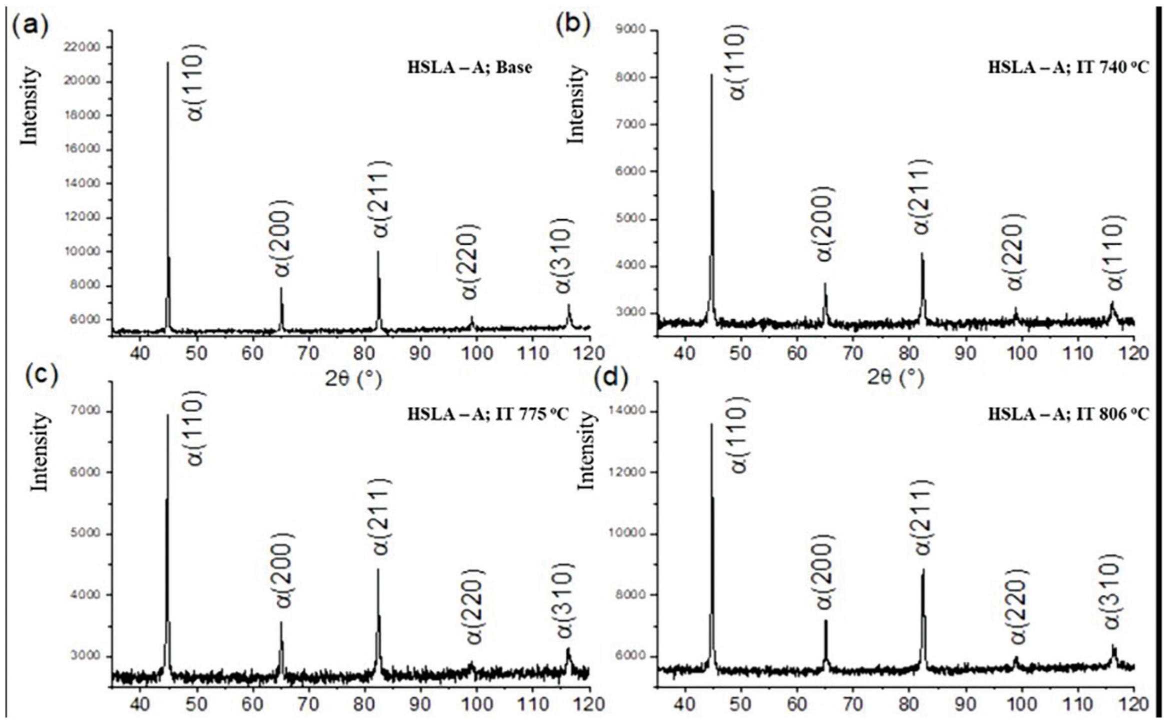

Figura 8: XRD of HSLA – A intercritical quenched steels.

Overall, our XRD results indicate the absence of austenite retained in martensite, where all the diffractograms corresponded to the ferrite pattern. This can be explained by the understanding of the influence of the temperatures of the martensitic transformation on the final microstructures. These finding indicate the inverse relation between the retained austenite content and the mechanical properties of the HSLA steels [24–29].

4. DISCUSSION

Steel is fundamental in the metal-mechanic industry and still has great potential for innovation and future research in various areas such as naval, automotive, and oil [4, 8].

With the growth of the Brazilian automotive market, attention is now focused on increasing the safety and efficiency of cheaper cars (popular cars).

In this sense, the search for more economical lightweight materials and processes has led Research & Development for the next 5 years of the ROTA 2030 Program [1, 3].

In this article, it was demonstrated that the chemical composition and the intercritical heating temperature were the most important parameters for obtaining dual phase steel microstructures [9, 12, 13, 19]. The higher speed of cooling in water resulted in a higher volume of martensite, and the volumes of polymeric solutions of 10%, 15%, and 20% had the same effects as the use of tempering oil [16, 17, 24–27]. With water cooling, the formation of a vapor film is favorable, leaving the transformation heterogeneous. The use of a polymeric solution with 5% polymer can be an alternative to obtaining higher martensite volumes [16, 17, 26]. The development of biodegradable polymers favors the reduction of evaporation losses and favors the thermal cycle with greater homogeneity in cooling directly passed to boiling and convection [26].

This way the volume of martensite will be evenly distributed in the matrix [9, 19].

The results also showed that small additions of alloying elements contributed to differences in carbon equivalent (CEA: 0.433 > CEB: 0.429 > CEC: 0.364) that significantly influenced the analyzed performance indicators. Emphasis on the influence of intercritical temperature variation on the % of martensite, after heat treatment, which presents the highest variation of F' in the statistical test (FT' = 67.71). This high F' value indicates a strong relationship. All samples show a biphasic microstructure after intercritical tempering. Additionally, samples B and C (740 °C) have some bainite content.

The tests and mechanical analyses show that sample A, after quenching at 740 °C, presents the best results for relative toughness (100%). Also, from the point of view of ANOVA, properties such as yield strength (YS), relative toughness, and elongation have the highest levels of significance. This exposes the strong influence of the heat treatment parameter and the final microstructure on the properties and performance of the materials [9, 12, 28–35].

In comparison with the base material, it can be observed that the intercritical heat treatment increases the performance of the materials in terms of preventing the antagonistic properties of the dual phase stel, with one exception being the HSLA – A samples. After being cooled to 806 °C, they present higher YS and TS values, but also show a large decrease in relative toughness. Must limit the application of high intercritical temperatures (Close to A3) for quenching HSLA steels by the effect of equivalent carbon.

It is important to note that, considering the number of applications of Biphasic Steels in the automotive, naval, and oil industries, it can be concluded that intercritical tempering contributes to obtaining superior properties, increasing efficiency, performance, and automotive sustainability.

In summary, the experimental results showed that the cooling of microalloyed steels with Nb and Ti obtained in the temperature ranges of the intercritical region can represent an important variable to guarantee the consistency of the austenitic grain size. In addition, we verified that the chemical elements Nb, V and Ti act mainly in the austenitic grain refining and in the precipitation during the steel processing. Our results showed that during the austenite grain refining process and the precipitation mechanisms, the presence of Nb, V, and Ti formed particles of carbides, nitrides, or a combination of both. This result, combined with the formation of precipitated carbonitrides, creates a fine dispersion in the matrix [36–41]. The presence of precipitates was confirmed by the presence of Nb, V, Ti, C, and N peaks using the XRD technique. Relationship between the hardening parameter and the final Dual Phase Steel microstructure.

The precipitates act as barriers to the movement of atomic dislocations, causing an increase in the mechanical strength of metallic materials [4, 7]. Steels with fine or extrafine austenitic granulometry and mechanical strength obtained by the microstructure of biphasic steels, present a significant increase in fatigue life [4]. This finding has important implications for the development of two-phase steels with higher mechanical properties and better fatigue behavior, maintaining grain refinement at different subcritical temperatures [4, 7]. Furthermore, these observed findings contribute to the literature on dual phase steel by comparing them with conventional structural steels [25, 32, 38].

Another scientific contribution derived from this research is the possibility of using mechanisms similar to those developed in the Tempcore process, making it possible to obtain a ferritic matrix with islands of martensite in controlled lamination with water-based polymeric solutions [39].

The vapor phase is eliminated using different cooling rates combined with polymeric solutions, directly causing boiling and convection, increasing the cooling rate. In this way, the microstructures of two-phase steel can be guaranteed [20, 35, 38, 40–44].

Finally, the study is not free of limitations, despite the singularity of the scope examined and the experimental results for the research on biphasic steels of microalloyed materials. A limitation to be studied in the future is related to the effect of silicon content in the intercritical zone. We also propose directions for future research that would be of interest to scholars and practitioners working in the fields of materials science characterization and materials technology. First, it would be interesting to verify the behavior of microalloyed two-phase steel at cryogenic temperatures. Second, additional research can investigate the fatigue behavior of two-phase microalloyed steels. Finally, studies applying the Gleeble thermomechanical simulation to microalloyed two-phase steels are suggested for future experiments to reproduce the same cycle of thermal and mechanical processes. The following section presents the main conclusions of the study.

5. CONCLUSIONS

The new advances in materials are of great importance in the industrial area. Due to the complete mastery of its manufacturing processes and thermal cycling capacity, it is possible to obtain improvements in its mechanical and metallurgical properties.

Our evidence confirms the potential benefits of adopting intercritical treatment and obtaining dual phase steel. In summary, the main findings allow the following conclusions and scientific implications for research and the use of materials for industrial applications:

- The presence of 1.43% manganese contributed to the increase in temperature at the beginning of the martensitic transformation. Other elements such as chromium, nickel, and molybdenum also significantly influenced the Andrews curves. However, the low concentration of these elements did not cause significant changes in the curves.
- In the analysis of the resulting microstructure, ferrite and pearlite were observed in the samples prior to the intercritical heat treatment. After intercritical treatment, the microstructure autonomously changed to a ferritic matrix with martensite islands at all examined levels. Furthermore, with an intercritical temperature of 740 °C, the presence of bainite was observed.
- The volumetric proportion of the second martensite phase reached 41%, with the highest intercritical temperature. The temperature variation from 806 °C to 775 °C did not indicate a significant difference, reaching a minimum difference of 0.6%. Furthermore, when the temperature was reduced from 775 °C to 740 °C, the lowest volumetric proportion of martensite was obtained, reaching a minimum value of 18%.
- The influence of the parameters in the intercritical treatment is noticeable due to the variation present in the second phase.
- The intercritical temperature is the parameter that caused the most significant change in the martensite volumetric fraction. This research finding has important implications because the higher the temperature, the greater the amount of martensite present.
- Analyzing the microhardness, the effectiveness of the intercritical treatment is verified, since the microhardness of the pearlite in the samples before the intercritical treatment was 282.67 HV0.01. Furthermore, after treatment, the microhardness reached 434.2 HV0.01, compatible with low-carbon site mink. As expected, the ferrite did not show significant variation in microhardness. Significant effects of microalloying elements were observed to obtain biphasic microstructures in biphasic steel.
- As the intercritical temperatures are lower than the growth temperature of the austenitic grains, consistency in the size of the austenitic grains was verified, which is associated with dynamic recovery and recrystallization of the microstructure.
- The mechanical tests demonstrated the effectiveness of increasing the mechanical strength of the two-phase steel obtained from the chemical composition of low carbon content and the microalloy elements Nb and Ti. Under these conditions, it was possible to anchor the austenitic grain size, maintaining adequate elongation, increasing yield and resistance limits. The tests and mechanical analyzes show that sample A, after quenching at 740 °C, presents the best results for relative toughness (100%).
- The use of polymers as a cooling medium minimized the formation of the vapor phase, increasing the severity of the martensitic transformation (low carbon martensite).
- Biodegradable polymers represent an ecological alternative with good performance in obtaining dual phase steel.

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