Analysis of the Effects of Straightening and Aging on the Mechanical Properties of Low and Medium Carbon Steel Wire

Análise dos Efeitos do Endireitamento e do Envelhecimento nas Propriedades Mecânicas de Fio-máquina de Aço Baixo e Médio Carbono

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ABSTRACT

The steel industry represents a sector of great importance in the production chain, being directly related to the economic development of the world. The straightening process, an important phenomenon of plastic deformation during steel production can bring changes in the results of mechanical properties. The goal of this study is to analyze the interaction between the variables involved in the natural strain ageing, straightening (manual and mechanical) and in the chemical composition (low and medium carbon steels) of the wire rod, being the variation of the mechanical properties - through the tensile test – and microstructural – from the microstructural characterization – the analysis parameters. The results indicate a trend towards an increase in the yield and resistance limits of the materials that were submitted to the straightening and strain aging process, and it is possible to notice the pattern, from the contour and response surface graphs, that the higher the levels of straightening and percentage of carbon, the higher the values of yield strength and resistance.

keywords   rolling, steel, physical metallurgy, aging, plastic deformation

RESUMO

A indústria siderúrgica representa um setor de grande importância na cadeia produtiva, estando diretamente relacionada ao desenvolvimento econômico mundial. O processo de endireitamento, importante fenômeno de deformação plástica durante a produção do aço pode trazer alterações nos resultados das propriedades mecânicas. O objetivo do trabalho foi analisar a interação entre as variáveis envolvidas no envelhecimento natural, endireitamento (manual e mecânico) e na composição química (aços baixo e médio carbono) do fio-máquina, sendo a variação das propriedades mecânicas – por meio do ensaio de tração – e microestrutura – a partir da caracterização microestrutural – os parâmetros de análise. Os resultados indicaram a tendência de aumento nos limites de escoamento e resistência dos materiais que foram submetidos ao processo de endireitamento e envelhecimento, sendo que se nota o padrão, a partir dos gráficos de contorno e de superfície de resposta, de que quanto maiores os níveis de endireitamento e percentual de carbono, maiores foram os valores de limite de escoamento e de resistência.

palavras-chave   laminação, aço, metalurgia física, envelhecimento, deformação plástica

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Introduction

The steel industry plays a vital role in the production chain of construction, automotive manufacturing, and infrastructure development, directly linked to the economic development of the world. In Brazil, revenues in 2021 reached US$ 38.7 billion, creating 114 thousand direct jobs. This revenue corresponds to 36 million tons of steel produced and 6 million tons of net steel exports, accounting for 7.1 % of Brazil trade balance (Empresa de Pesquisa Energética, 2022; Konak & Kamaci, 2019). In 2023, Brazil produced 32.0×10^6 t of crude steel which represents 35 % of all the sales of steel products in the foreign market a total of 31.128×10^3 t (Instituto Aço Brasil, 2024).

Due to the relevance and growth of the steel sector, it is important to analyze, compare and measure its production, focusing on the customer. As one of the pillars of the steel industry, they are strong allies for the quality of commercial process and competitiveness in this sector through environmental compliance (Lin et al., 2023; Prasad & Mishra, 2017). In this context, the present work aims to expand knowledge about the behavior of two groups of wire rods – low and medium carbon – through straightening and aging which are common metallurgical phenomena in the steel industrial process.

The straightening process, an important phenomenon of plastic deformation, can alter mechanical properties according to Daroit (2012), due to the hardening of the material in the plastic deformation process. Similarly, aging, according to Leslie (1982 as cited in Meira, 2020, p. 17), involves changes of metal characteristics, such as increased strength and decreased ductility in specific contexts. Thus, it is essential to analyze the interaction between these variables in steels with different chemical compositions, as well as to understand the resulting changes in mechanical properties, including yield limit and resistance, in addition to ductility (based on percentage elongation).

In routine industrial production, manual straightening is the most common and applicable, due to its speed and ease compared to the mechanical one. The principle of manual straightening consists of inserting the curved sample into the holes of the manual straightener. Force is then applied in the direction of the curve repeatedly until the sample is completely straightened. In mechanical straightening the source of stress is the straightening machine (Mischke & Jonca, 1992). The result of the process depends on several factors, including the curvature of the rolls, material properties, angle, distance and pressure between the rolls, the structural flexibility of the straightening equipment, and the pre-defined conditions for each roll (Bader et al., 2022).

The aging process can be defined, in simplified terms, as the set of changes in the properties of a metal resulting from interactions between dislocations and interstitial solute atoms due to plastic deformation. According to Wright (1996 as cited in Brito, 2018, p. 25), the fixation of dislocations, caused by interactions with carbon and/or nitrogen atoms, is the primary factor contributing to the aging phenomenon in steels (Nicolodi, 2021). Eder (2006) notes that while aging can be viewed as a detrimental process for the industry, it can also serve as a valuable mechanism to enhance the strength of materials.

This work aims to examine the interaction between natural aging and straightening phenomena in the chemical composition of wire rod. The comparison process will be based on two types of straightening: manual and mechanical. Additionally, the carbon content will be varied between low carbon steel (SAE 1005) and medium carbon steel (SAE 1042). Aging will occur by allowing the material to rest after the plastic deformation caused by straightening, and measurements will be obtained through a series of tensile tests.

Materials and methods

The first aspect of analysis, straightening was subdivided into two comparative groups: manual straightening (mild) and machine straightening (intense). The chemical composition variable was also subdivided into two study groups based on the percentage of carbon: medium carbon steel – 1042 and low carbon steel – 1005. Finally, the last variable evaluated was the influence of static aging after straightening which was observed through changes in the mechanical properties of steels over time. The evaluation period lasted 38 days, during which 11 measurements were taken. The measurement days were selected based on the availability of the testing machine for routine tests at the plant, to ensure precise monitoring of variations in the measured properties. The work planning is illustrated in the flowchart in Figure 1.

Figure 1 - Descriptive planning used in the work.
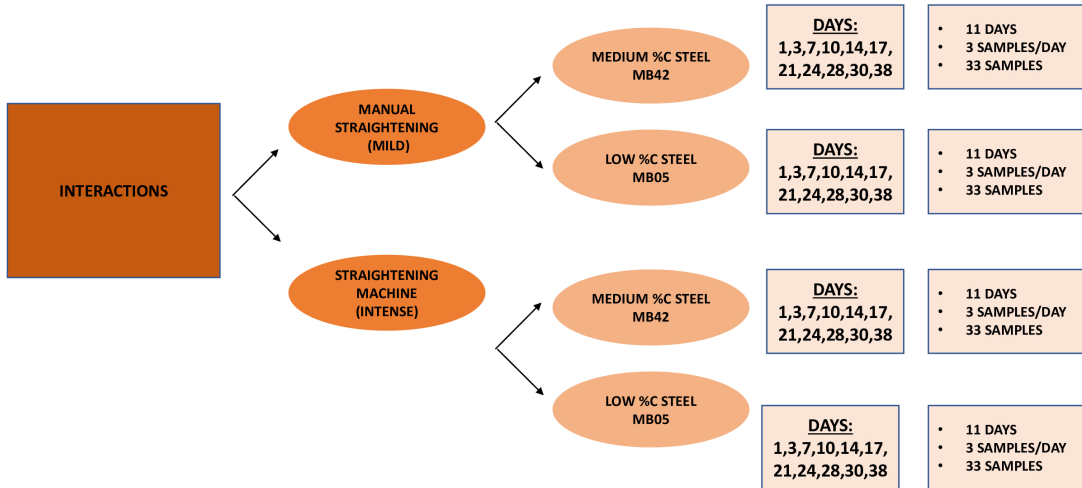
The resources and structure used in the research belong to the ArcelorMittal Group and the Laboratories of the Metallurgy Center of the Federal Institute of Sudeste Minas Gerais – Juiz de Fora Campus. The materials and resources needed in the process of collecting and preparing the wire rod samples were: 6.5 mm wire rod coil, rebar cutting scissors, and FORMAT 12 HS model stirrup.

In the testing phase, the following materials and resources were utilized: a 20T Ultimate Tensile Machine (Panantec model), a 100 mm digital caliper, a digital micrometer and a 6.30 mm sample scribe pattern. For the laboratory analysis of the samples, the following materials and resources were used: a cutting machine (Arotec – model Arocor 80), a sanding machine (Buehler – model Ecomet 4000), sandpaper with grit sizes 80, 120, 400 and 600 (Norton model), an embedding machine (Buehler – SimpliMet 1000 model), a polisher (Buehler – Ecomet 4000 model), diamond paste of 0-2 micron and 3-6 micron (Christensen Roder model), 5 % nitaletching reagent, and an optical inverted platinum microscope (Olympus – model GX 51F). To determine the carbon content, a spectrometer from the manufacturer ThermoFisher SCIENTIFIC (model ARL4460) was employed.

Regarding the removal of samples, as the roll entered the quality control sector, the coils were removed from both the AISI 1005 and the AISI 1042 steel roll. First, the samples were removed using the standard disposal method – discarding samples from the head and/or tail of the roll to eliminate defects inherent to the rolling mill production process. As a result, 80 coils were removed from the grades 1005 and 1042 wire rod rolls, 40 from each. Given that each coil generates 5 samples, a calculation was made to obtain around 400 samples to allow for a margin of error and unforeseen events.

The quality inspectors removed the coils using pressure scissors. Alongside the coils, three control samples were taken from each roll (totaling six samples, three from SAE 1005 materials and three from SAE 1042 materials) as represented in Figure 2. The objective of obtaining these control samples was to establish a parameter of the mechanical properties of the material before conducting all straightening and aging manipulations. After cutting the coils, the material was stored on the coils line.

**Figure 2 -** Sample removal procedure along the roll.

For mild straightening (manual), illustrated in Figure 3, the samples required manual cutting using rebar cutting scissors. These samples were cut to a length of around 550 mm. This value considers a distance between 340 mm plus approximately 110 mm of material fixed in the Universal Tensile Machine. After this, the samples underwent manual straightening.

Figure 3 - Manual straightener.

For intense (mechanical) straightening, the preparation process consisted of cutting the group of 40 coils in half (20 coils) and labeling them to prevent mixing of materials. Upon completion of the straightening process, approximately 200 samples of SAE 1005 steel and 200 samples of SAE 1042 steel were was obtained. After straightening, the wire rods were set aside for the test. Figure 4 shows the samples: those straightened manually (mild) on the left, the samples and those straightened mechanically (intense) on the right.

Figure 4 - Samples reserved after straightening: (a) manually; (b) mechanically.

(a)   (b)
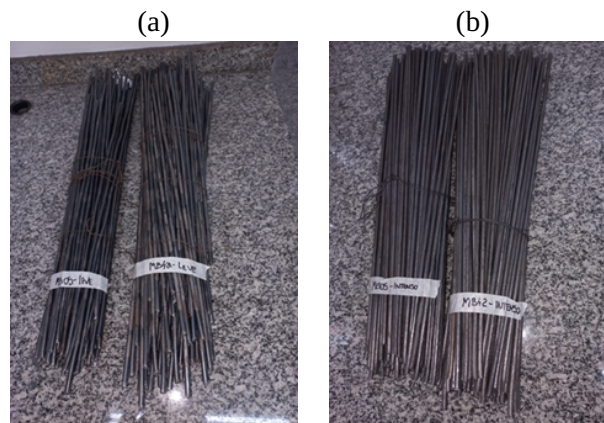
After the straightening process, the first step was to identify the samples using codes. Table 1 illustrates the coding system, in which 'X' represents the sample number (ranging from 1 to 3) and 'Y' the day number (ranging from 1 to 38). The samples were subjected to a tensile test at a pre-determined standard speed of 20 mm/min using the NBR 7480 standard for measuring elongation.

Table 1 - Details of the sample codes.

Code	Straightening	% Carbon	Day
LBXDY	L-MILD	B-LOW	Y-DAY
LMXDY	L-MILD	M-MEDIUM	Y-DAY
IBXDY	I-INTENSE	B-LOW	Y-DAY
IMXDY	I-INTENSE	M-MEDIUM	Y-DAY

Microstructural characterization was conducted to observe the wire rods structures before and after straightening and to determine if grains elongation occured due to hardening. For this microstructural analysis, metallography was performed on six samples.

Results and discussion

The microestructure of the SAE 1005 and 1042 steels can be observed in the cross-sectional optical microscopy images, Figures 5(a) to 5(d). Both compositions in the images show the microstructure predicted by the CCT diagram for hypoeutectoid steels thermally treated under continuous cooling. The presence of a microstructure was perceived as composed of bright grains of proeutectoid ferrite and darker grains of pearlite. Such behavior was observed by Miranda (2021) in his work on natural aging.

Figure 5 - Optical microscopy of the longitudinal section of 6.5 mm wire rod; (a) low carbon after mild straightening; (b) medium carbon after mild straightening; (c) low carbon after intense straightening; (d) medium carbon after intense straightening, nominal magnification of 200×, nital 5 %.

(a)　　　　　(b)

(c)　　　　　(d)
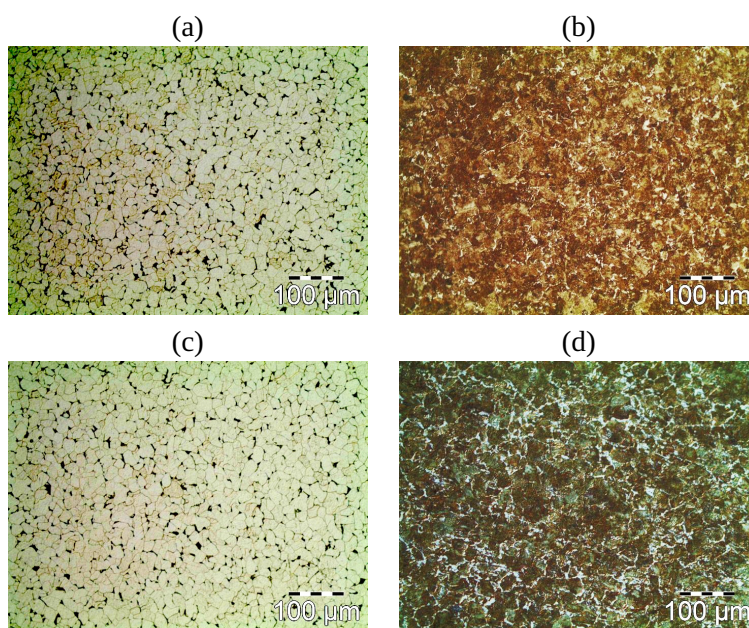
Regarding the comparison between wire rods before and after the straightening process, several key aspects emerge, including the microstructural evaluation. In relation to the phases, there is a distinction between the percentage of pearlite in low carbon steels – 0.05 % C and medium carbon steels – 0.42 % C. It's observed that medium carbon steel has a higher proportion of perlite than low carbon.

Another aspect to evaluate in the comparison of wire rods before and after the straightening process is the elongation of the grains in each steel type. Arrais (2019) and Yamasaki (2018), have shown that materials subjected to cold forming often exhibit noticeable grain elongation in longitudinal sections. Although cold forming was not utilized in this study, straightening applies localized stresses that can cause deformations.

Thus, it is important to assess whether these stresses lead to significant grain stretching. However, the results indicate no substantial difference in grain elongation between the steel compositions or across the different types of straightening. This lack of noticeable elongation can be attributed to the localized nature of the applied stresses, which were insufficient to cause significant grain stretching.

In low and medium carbon steel, the primary effect observed was the change in tensile strength an elongation percentage afterstraightening. Table 2 summarizes these changes, comparing values from day 0 (the day of production – before straightening, represented by the "Prior" column) to day 1 (24 hours after straightening, represented by the "After" columns).

In general, it was possible to observe, after the straightening and aging process, a tendency for tension to increase, both in the yield limit and in the resistance limit. In the case of the mechanical property of percentage elongation, there was a tendency for values to decrease. This aligns with the finds of Miranda (2021) in his study on natural aging, the author considers that the characteristics of increasing yield limits, resistance, and reducing the ductility of the material are common aspects of the deformation process.

The localized hardening, indicated by a increased mechanical resistance and decreased elongation, was more pronounced in SAE 1005 steel after intense straightening and in SAE 1042 steel after mild straightening. A similar behavior was observed by Zamani et al. (2018) for low carbon steel aged at room temperature.

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Table 2 - Mechanical behavior of the samples after straightening.

Steel	Parameters	Straightening		
			Mild	Intense
		Prior	After	After
SAE1005	σ_y	285 ± 4	292 ± 2	380 ± 6
	σ_R	409 ± 3	413 ± 1	428 ± 5
	$\%\epsilon$	35 ± 1	36 ± 4	30 ± 1
SAE1042	σ_y	492 ± 2	514 ± 3	496 ± 4
	σ_R	747 ± 2	779 ± 3	749 ± 1
	$\%\epsilon$	20 ± 1	17 ± 3	16 ± 1

Figures 6 and 7 respectively show the effect of static aging on the mechanical strength of SAE 1005 and SAE 1042 steel.

Figure 6 - Mechanical behavior of SAE 1005 steel as a function of aging time: (a) σ_y, mild straightening; (b) σ_y, intense straightening; (c) σ_R, mild straightening; (d) σ_R, intense straightening; (e) $\%\epsilon$, mild straightening; (f) $\%\epsilon$, intense straightening.
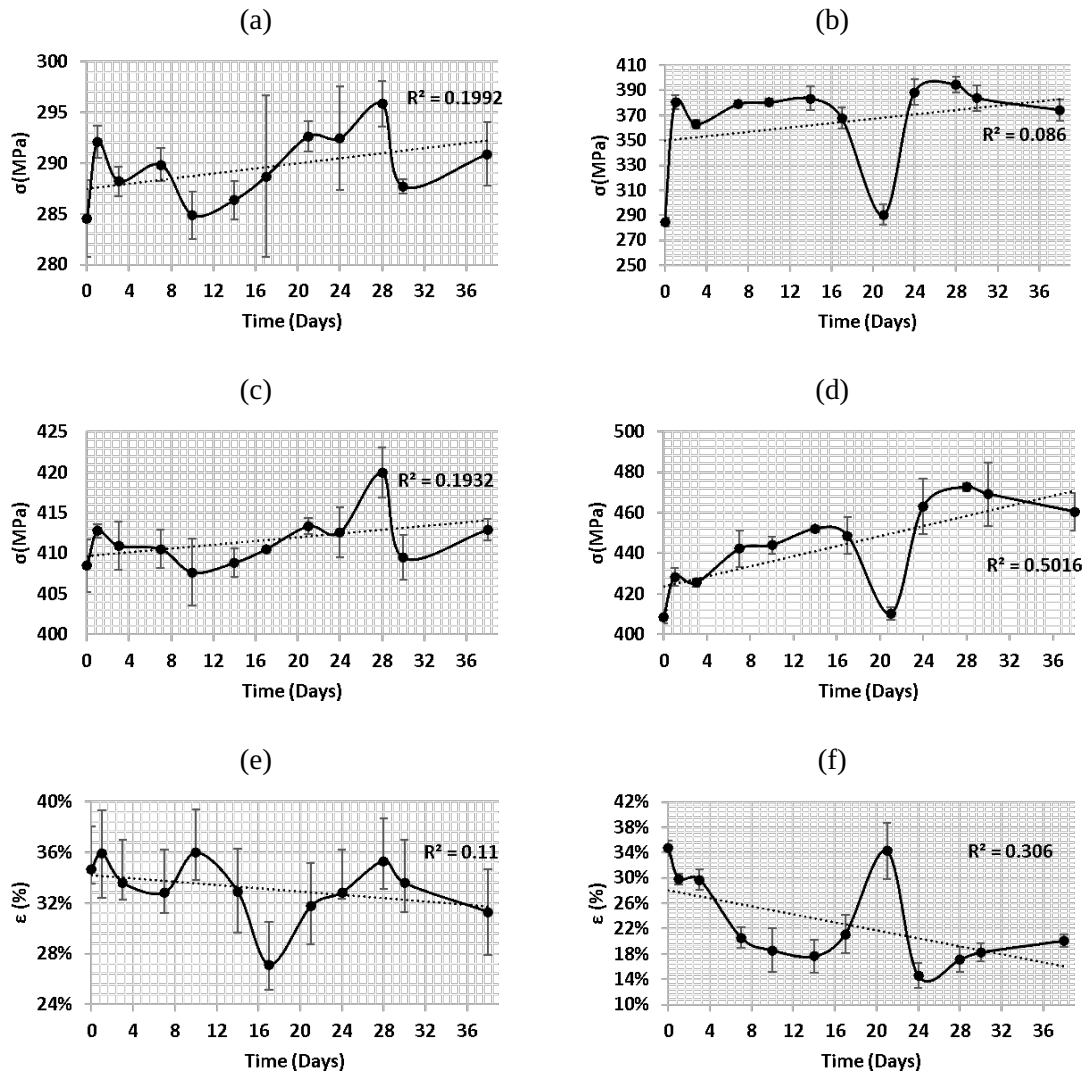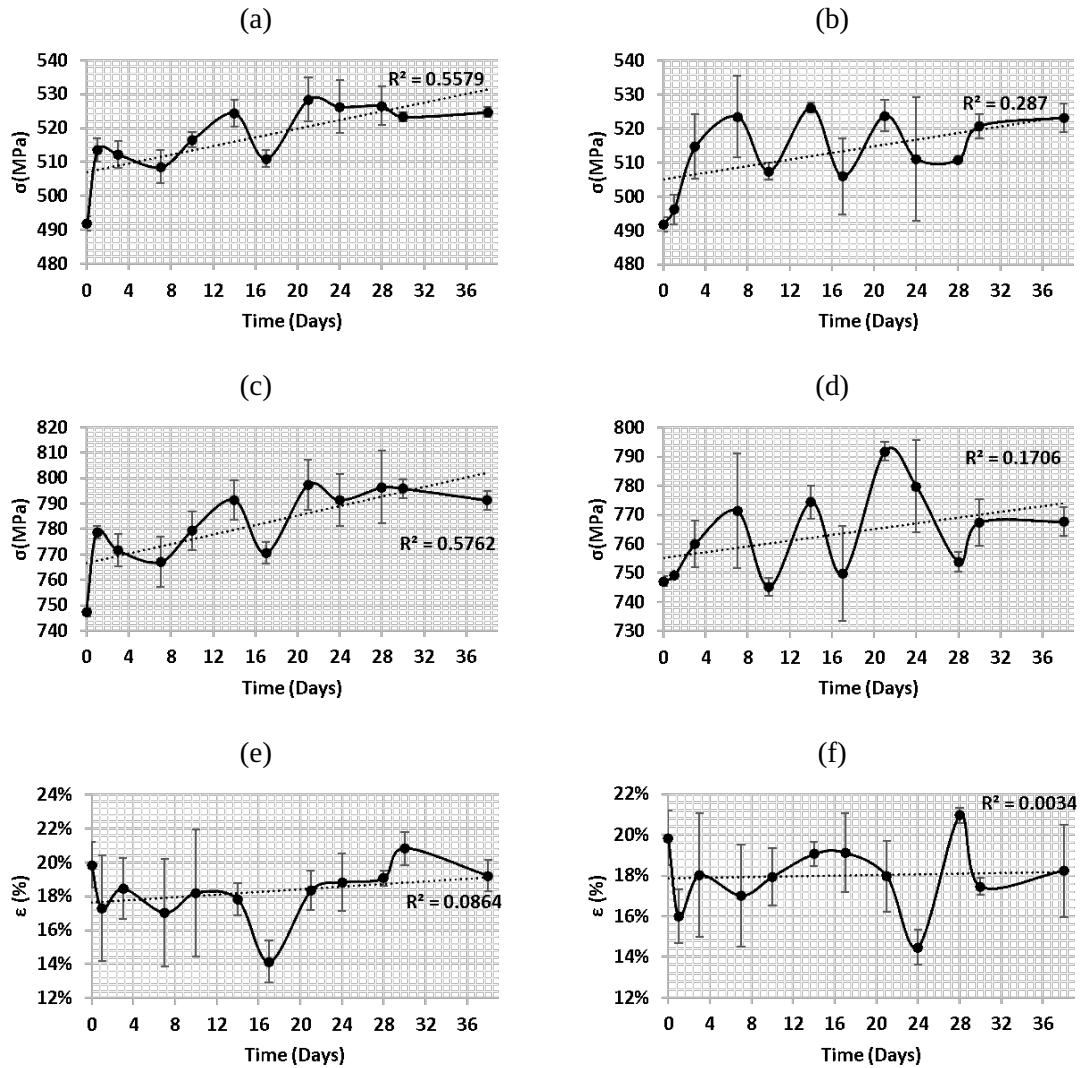

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Figure 7 - Mechanical behavior of SAE 1042 steel as a function of aging time: (a) σ_y, mild straightening; (b) σ_y, intense straightening; (c) σ_R, mild straightening; (d) σ_R, intense straightening; (e) $\%\epsilon$, mild straightening; (f) $\%\epsilon$, intense straightening.

Regarding the aging process, Figures 6(a) and 6(b) shows that, comparing day 3 and day 38, for example, it can be seen that, considering the SAE 1005 steel, the slight straightening brought slight trends of gain in yield limits (around 3 ± 5 MPa – approximately 0.9 %) and the intense straightening followed a slightly more expressive trend of gain in σ_y (around 11 ± 12 MPa – approximately 3 %). In Figures 7(a) and 7(b), which is related to SAE 1042 steel, the straightening brought slight trends towards gains in yield limits. For mild straightening, the gain was around 12 ± 5 MPa – approximately 2.5 % - and for intense straightening the gain trend was around 9 ± 13 MPa – approximately 1.6 %. These findings are consistent with Zamani et al. (2018) observations on the mechanical properties of low carbon dual-phase steel through natural aging.

Regarding the resistance limit, Figures 6(c) and 6(d), a similar trend can be observed in the yield limit. Specifically, there is an increase in stress values when comparing days 0 and 1, as shown in Table 2. The stress gain is 4 ± 4 MPa (approximately 1 %) for the mild case and 19 ± 8 MPa (approximately 5 %) for the intense case, indicating that the gain in intense straightening is five times greater in mild straightening. Concerning to the aging process, it can be stated that, in the case of SAE 1005 steel, mild straightening brought slight trends towards gains in resistance limits (around 2 ± 4 MPa – approximately 0.5 %) and intense straightening followed a considerably significant trend towards gain in σ_R (around 35 ± 12 MPa – approximately 8 %).

As the density of dislocations increases, the resistance to the movement of these defects becomes more pronounced, generating an increase in the tensions necessary for flow to occur and for the resistance limit to

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be reached in the tensile test (Jin et al., 2018). Therefore, the material that underwent mild straightening is expected to have a lower level of 'activated' dislocations compared to the intensely straightened steel. Consequently, the tension gain in the mildly straightened material will be lower than that observed in the intensely straightened one.

Overall, the curves depicting the variation in the mechanical properties analyzed over time do not provide a comprehensive overview of the interaction between chemical composition, straightening, and aging, despite the presented R^2 values, indicating that the results did not follow a linear regression model.

Consequently, the approach for evaluating trends, interferences, and interactions between variables will be factorial planning. Factorial planning was employed to identify which factors most significantly affect the interaction between chemical composition, straightening, and aging.

This analysis was conducted using Minitab software and utilized two tools: contour plots and response surfaces. However, according to Melo et al. (2017) and Moreira et al. (2023), statistical theory brings the value "p" – which varies between 0 and 1 – as a parameter of the statistical significance of a sampling process, and only when p is less than or equal to the value of 0.05, the results of the studies are considered significant. Therefore, before constructing the curves and surfaces, an analysis of the significance of the data obtained in the Minitab software was carried out, summarized in Table 3.

Table 3 - Assessment of statistical significance of data.

Factors	p
Straightening $\times$ carbon content: σ_R	0.000
Straightening $\times$ carbon content: σ_R	0.000
Straightening $\times$ carbon content: $\epsilon\%$	0.024
Straightening $\times$ aging: σ_R	0.982
Straightening $\times$ aging: σ_R	0.947
Straightening $\times$ aging: $\epsilon\%$	0.457
Aging $\times$ carbon content: σ_R	0.896
Aging $\times$ carbon content: σ_R	0.700
Aging $\times$ carbon content: $\epsilon\%$	0.050

It is observed that, according to theory, only the first three and the last interactions have statistical significance – p values less than or equal to 0.05 – so, only the complete group of "straightening" type interactions was analyzed.

Analyzing the interaction between the variables carbon content and straightening at the yield limit, see Figure 8, it is observed that, in general, the higher the level of straightening and the carbon content, the higher the yield limit values.

Figure 8 - Variables straightening and carbon content, in relation to σ_y: (a) response surface graph; (b) contour graph.
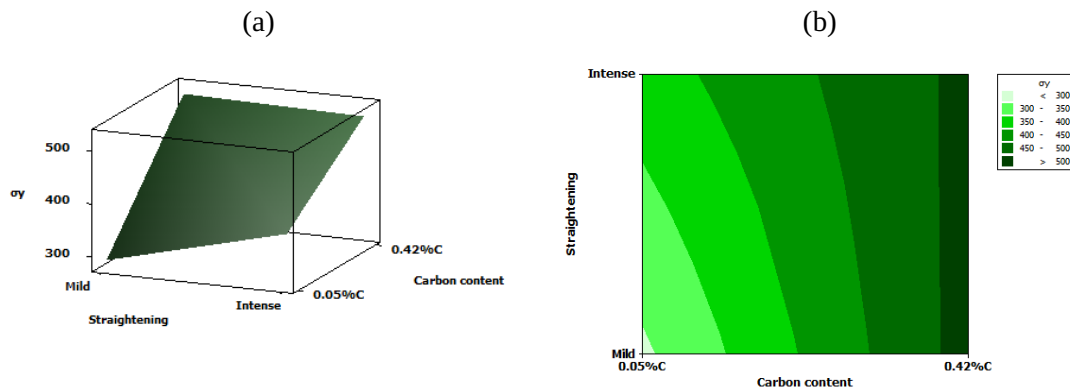
Regarding to the interaction between the variables carbon content and straightening at the resistance limit, Figure 9, it is also observed that, in general, the higher the level of straightening and the carbon content, the higher the limit values will be of resistance.

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Figure 9 - Straightening and carbon content variables, in relation to σ_R: (a) response surface graph; (b) contour graph.
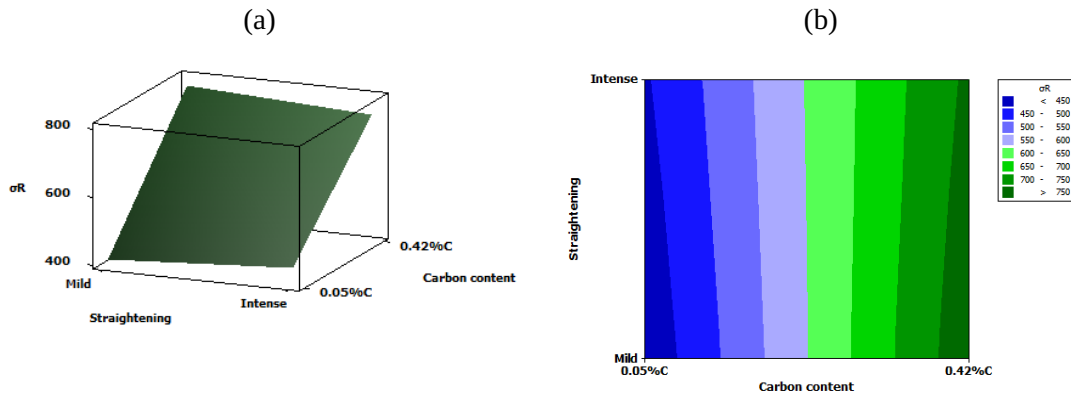

Such results are in line with what was predicted in the bibliographies, based on the consideration of Dieter (1982), for example, on the process of plastic deformation, in which it is said that as the deformation occurs, the sliding and the multiplication of dislocations are being activated and intensified, which causes regions of high dislocation density to emerge.

This scenario generates a thermodynamic and kinetic context conducive to the formation of Cottrell atmospheres and, consequently, an increase in yield stresses and resistance when the material is subjected to the tensile test. Therefore, it is expected that the material that has undergone mild straightening will have a lower level of "activated" dislocations than the intensely straightened steel, which means that there will be a lower stress gain in the mild straightening material.

Regarding the interaction between the variables carbon content and straightening in the percentage of elongation, Figure 10 it is also observed that, in general terms, the higher the level of straightening and the carbon content, the lower the percentage values will be of stretching.

Figure 10 - Variables straightening and carbon content, in relation to the percentage of elongation: (a) response surface graph; (b) contour graph.
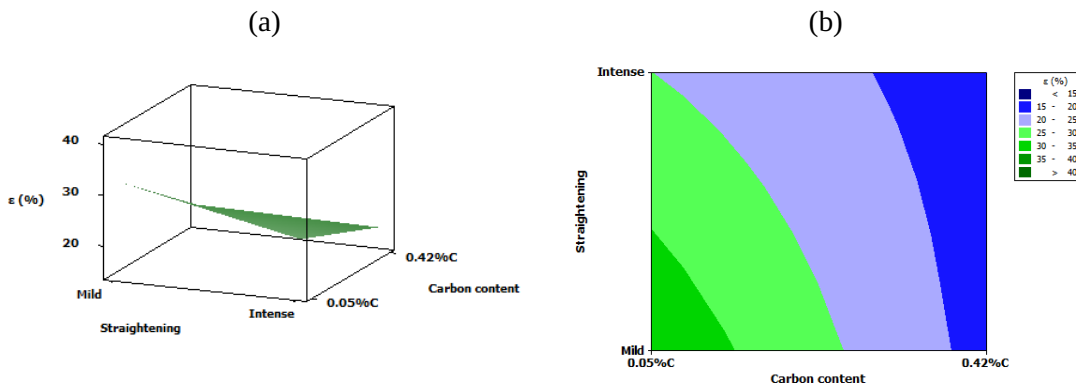
Conclusions

Analyzing the results of this study, it was observed the effects of straightening and aging on the mechanical properties of low and medium carbon wire rods. Regarding straightening, there was a tendency for both yield strength and resistance to increase in materials subjected to this mechanical deformation process.

Notably, both manual and mechanical straightening did not induce microstructural changes, as there was no difference in the elongation of the grains between the two chemical compositions of steel across the different straightening methods. This behavior can be attributed to localized plastic deformation during the straightening process.

Regarding the interaction between straightening, aging and carbon content, factorial planning emerged as the most effective method for identifying the factors with the greatest influence on these variables.

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This was particularly evident from the R² values, which showed less consistency when analyzing the mechanical property curves (σ_y, σ_R, and ductility) over time.

Additionally, some interactions were found to be statistically insignificant, indicating the need for a larger sample size and extended testing periods to better assess the mechanical properties.

Overall, the contour and response surface graphs reveal a clear trend: higher levels of straightening and carbon content lead to increased yield strength and resistance, while higher levels of these factors correspond to lower elongation percentages.

Acknowledgments

Author contributions

M.M. Candido Neto participated in the conceptualization, formal analysis, investigation, visualization writing and editing. M.J.C de Oliveira participated in: conceptualization, formal analysis, investigation, visualization and writing.

Conflicts of interest

The authors certify that no commercial or associative interest represents a conflict of interest concerning the manuscript.

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