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The influence of different heat treatment cycles on the properties of the steels HARDOX® 500 and STRENX® 700

A influência de diferentes ciclos de tratamento térmico nas propriedades dos aços HARDOX® 500 e STRENX® 700

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Abstract

The HARDOX® 500 and STRENX® 700 steels are quenched materials from hot rolling process. The HARDOX® 500 is a low alloy steel with high values of microhardness and mechanical strength, the STRENX® 700 steel is a low alloy steel structural used in applications, where low density is associated with high mechanical strength. In this work, the two steels were submitted to different heat treatments: quenched and tempering, normalization and full annealing. The effects of these heat cycles were analyzed by optical microscopy and Vickers microhardness techniques. It was concluded that in the normalization treatment, the microhardness reduction of HARDOX® was more significant than that one of STRENX®. In the quenched and tempering process, both presented higher microhardness compared to the originally produced and characterized material with higher austenitic grain refining. The HARDOX® presented an effective increase of microhardness. In the heat treatment of full annealing, the HARDOX® 500 and the STRENX® 700 steels had similar microhardness and microstructural morphology values.

Keywords: HARDOX® 500. STRENX® 700. Heat treatments.

Resumo

Os aços HARDOX® 500 e STRENX® 700 são materiais temperados, a partir do processo de laminação à quente. O HARDOX® 500 é um aço de baixa liga com valores elevados de microdureza e alta resistência mecânica e o aço STRENX® 700 um aço de baixa liga estrutural utilizado em aplicações, onde baixa densidade é associada à alta resistência mecânica. Neste trabalho, os dois aços foram submetidos a diferentes tratamentos térmicos: têmpera e revenido, normalização e recozimento pleno. Os efeitos desses ciclos térmicos foram analisados, através das técnicas de microscopia óptica e microdureza Vickers. Concluiu-se que, no tratamento de normalização, a redução de microdureza do HARDOX® foi mais significativa do que o do STRENX®. Já no processo de têmpera e revenido, ambos apresentaram microdureza superior comparado ao material originalmente fabricado e caracterizado com maior refino de grão austenítico. O HARDOX® apresentou um aumento efetivo de microdureza. No tratamento térmico de recozimento pleno, os aços HARDOX® 500 e o STRENX® 700 tiveram valores de microdureza e morfologia microestrutural semelhantes.

Palavras-chave: *HARDOX® 500. STRENX® 700. Tratamentos térmicos.*

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1 Introduction

HARDOX and STRENX steels are produced in to meet microstructures, hardness and mechanical resistance related to tribological aspects such as wear. However, the chemical composition of these materials presents variations that can influence their hardenability. Due to the need for intermediate mechanical manufacturing processes during fabrication such as: welding and machining, these materials are subject to thermal inputs that influence their mechanical and metallurgical properties. From these conditions, it is of relevance to the evaluation of the mechanical and metallurgical properties of these steels and their behavior, after the application of different thermal cycles.

Heat treatments are conceptually the processes used to obtain better mechanical properties and to refine metallurgical properties in different ferrous and non-ferrous metals. With the development of new materials, there is an increasing need to understand the mechanisms associated with heat treatments. Therefore, in this essay, the behavior of HARDOX® 500 and STRENX® 700 steels was analyzed after the application of three different thermal cycles and cooling rates, verifying their effects on the microstructure and microhardness.

2 Bibliographic review

HARDOX® steels were developed by the Swedish company called Swedish Steel AB (SSAB). They have a microstructure consisting basically of tempered martensite and are characterized by high hardness and tensile strength. They are used in situations that require high resistance to wear (PONTEL, 2016). Due to the existing combination of high hardness, high mechanical resistance and excellent impact resistance, HARDOX® has been used in tipper dump trucks, allowing simpler and lighter constructions and, at the same time, supporting high loading loads (CORREA, 2017).

The fine-grained martensitic microstructure of this steel generates high mechanical strength, hardness and abrasion resistance. These properties are obtained through the strict balance of the chemical composition, besides presenting low levels of phosphorus and sulfur (BIALOBRZESKA; KOSTENCKI, 2015).

The table 1 shows the maximum values of the alloy elements that compose the steel.

Table 1 – Chemical composition of the steel HARDOX® 500

Alloying element	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Mo**	**B**
Maximum amount (%)	0,27	0,50	1,60	0,025	0,010	1,20	0,25	0,25	0,005

Source: Adapted from SSAB (2018a).

STRENX® 700 steel is a structural steel that has a minimum yield strength between 650 to 700 MPa, depending on the thickness of the plate and the cooling rate (PROCHENKA; MAKOWSKA; JANISZEWSK, 2018).

According to Mazur and Ulewicz (2017), this steel is manufactured through hot forming, where the heating, rolling, and cooling processes are carefully supervised.

According to Prochenka, Makowska and Janiszewsk (2018), because of its favorable ratio between strength and deformation, this steel can be subjected to cold forming allowing the manufacture of light structural elements characterized by high mechanical resistance.

In table 2, it is showed the maximum values of the alloy elements that compose the steel.

Table 2 - Chemical composition of the steel STRENX® 700

Alloying element	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Cu**	**Ni**	**Mo**	**B**
Maximum amount (%)	0,20	0,60	1,60	0,020	0,010	0,80	0,3	2,0	0,7	0,005

Source: Adapted from SSAB (2018b).

Heat treatment is the set of heating, temperature maintenance and cooling operations to which the materials are subjected, under controlled conditions of temperature, time, atmosphere, and cooling speed, with the aim of modifying their properties or giving them determined characteristics.

Annealing aims to reduce steel hardness and increase ductility to facilitate cold working or achieve the desired microstructure or properties. There are three types of annealing: full annealing, subcritical annealing / stress relief and spheroidization. The full annealing temperature is about 50 ° C above the austenitization temperature (SILVA; MEI, 2010). Upon full annealing, the steel is heated to the austenitization temperature and cooled in the oven.

The lower is the austenitization temperature, greater are the chances of nucleation of carbides and the subsequent growth of these undissolved carbides. Consequently, higher temperatures should be preferred when pearlitic structures are desired and lower when spheroidized structures are desired (SILVA; MEI, 2010).

Annealing has three stages, namely: dynamic recovery, recrystallization and grain growth. Dynamic recovery occurs at low temperatures with a dislocations rearrangement to acquire more stable configurations, reducing the stresses induced during hardening. Recrystallization occurs at higher temperatures than dynamic recovery and consists of the appearance of new and tiny crystals of identical structure to the non-deformed grains. Grain growth consists of an increase in grain size and a consequent decrease in mechanical strength.

Quenching is an adifusional heat treatment of high importance, because it is through it, accompanied by tempering. The properties are obtained that allow the use of steel in more critical components and applications, such as those found in the mechanical, transportation and aerospace industries and other industrial segments.

The quenching operation aims at the formation of martensite through rapid cooling, from the austenitization temperature in a medium of great cooling capacity such as: brine, oil, polymers and, occasionally, air. This process generates internal stresses in the material that must be immediately relieved or eliminated to return the necessary balance to the steel, while increasing the ductility which, after quenching, is practically canceled. This is achieved through the tempering operation.

According to Silva and Mei (2010), quenching causes temperature gradients that, associated with the contraction of steel during cooling, and the expansion associated with martensitic transformation and stress concentrators, causes internal stresses. Depending on the intensity of these stresses, deformations, cracks, and residual stresses can occur.

The tempering consists of reheating the quenched parts at temperatures below the starting temperature of the intercritical zone in hypopeutectoid steels and, depending on the applied, large or small changes, may occur in the microstructure:

- Between 160 ° C and 200 ° C - There are no sensitive structural changes, when attacked, they look identical to the original at lower temperatures and, at higher temperatures, they appear darker, this structure being called martensite tempered at low temperature;
- Between 200 ° C and 260 ° C - The steel starts to lose hardness, however, without noticeable structural modification;
- Between 260 ° C and 360 ° C - the precipitation of fine carbides begins, forming very fine pearlite.

There are two temperature ranges favorable for increasing the toughness for steels: 150 ° C to 200 ° C, in which there is a slight increase in toughness and above 425° C, in which there is a great increase in toughness, however, at cost mechanical strength and hardness.

Normalization consists of complete austenitization of the steel, followed by air cooling. It is indicated, after hot mechanical conformation and before quenching or tempering (SILVA; MEI, 2010). The normalization aims to refine and homogenize the steel structure aiming at grain size 5 or finer, according to the ASTM standard E 112.

3 Materials e methodology

The materials used in this essay were samples of HARDOX® 500 and STRENX® 700 steel. All samples were preliminarily analyzed using optical microscopy and Vickers microhardness test.

The samples of each material were subjected to a full annealing heat treatment, in which they were placed in an oven at a temperature of up to 50 ° C above the austenitization temperature. It was maintained at that temperature until complete austenitization of the material occurred and then cooled at a low rate (inside the oven).

For the quenching and tempering treatment, the samples were placed in the oven at the austenitizing temperature of 880 ° C, maintained until complete homogenization of the core and surface occurs and then cooled with a high rate in a polymer at 10% in aqueous solution in to obtain a martensitic microstructure. Subsequently, it was submitted to the tempering treatment at 180 ° C for one hour. For the normalization heat treatment, each material remained in the oven until complete austenitization at 880 ° C and was subsequently cooled in air.

Subsequently, the samples were analyzed, using optical microscopy and optical emission spectrometry, using the normal procedures of grinding metallography, polishing to obtain a flat surface. Subsequently, a chemical attack with Nital reagent at 3% was applied. Microstructural analysis was performed, using an OLYMPUS GX51 optical microscope. The microhardness of the samples, on the other hand, was evaluated, using a Vickers microdurometer with a load of 0.3 kgf, for 10 seconds.

4 Results and discussions

Initially, the characterization of HARDOX® 500 and STRENX® 700 steels performed without any heat treatment, that is, as received.

Through the spectrometry test, it was possible to obtain the chemical composition of HARDOX® 500 steel presented in table 3.

Comparing the results and the composition of each alloying element provided by the manufacturer, it is possible to notice that the basic elements from the manufacture of steel with Carbon, Silicon, Manganese, Phosphorus and Sulfur were found within the specified, the same occurring with the alloy elements. There was a high degree of purity in steel due to the reduced volume of harmful elements such as: sulfur and phosphorus.

Table 3 – Chemical composition of the HARDOX® 500 steel obtained through optical emission spectrometry

Alloying element	C	Si	Mn	P	S	Cr	Ni	Mo	B
%	0,215	0,234	0,675	0,0023	0,0007	0,569	0,089	0,029	0,0003

Source: The authors (2019).

The sample characterization of STRENX® 700 steel was performed, using the same method used for the HARDOX® 500 steel, being presented in table 4.

Comparing the chemical composition, obtained in the spectrometer and the maximum composition, provided by the manufacturer, it was possible to verify that most of the alloying elements showed levels within the specified. However, elements like Nickel and Molybdenum showed residual levels, the undesirable elements phosphorus and sulfur showed very low levels, which increased the steel's hardenability.

Table 4 - Chemical composition of the STRENX® 700 steel obtained through optical emission spectrometry

Alloying element	C	Si	Mn	P	S	Cr	Cu	Ni	Mo	B
%	0,17	0,31	1,23	0,0009	0,0007	0,35	0,01	0,05	0,146	0,001

Source: The authors (2019).

After the attack with nital at 3%, images were obtained through the optical microscope. Figure 1 shows the micrographs of HARDOX® 500 and STRENX® 700 steel in the received condition and, after the heat treatments of full annealing, normalized and quenched and tempered.

Resembling the HARDOX® 500 steel, the STRENX® 700 in the receiving condition presented the tempered martensite microstructure, showing that the samples had already undergone quenching and tempering heat treatment.

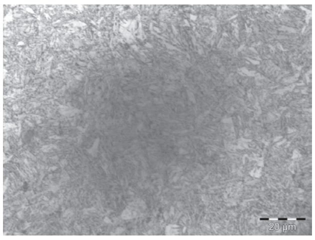
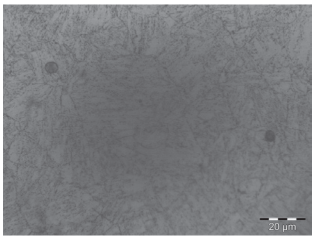
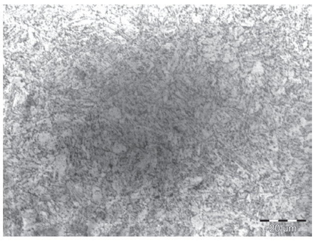
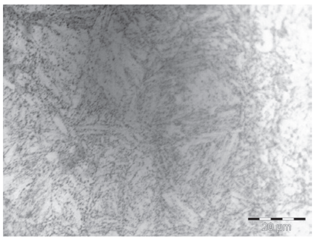
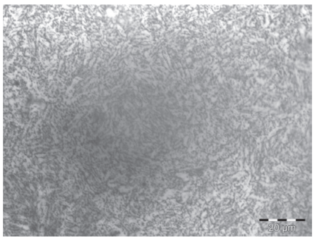
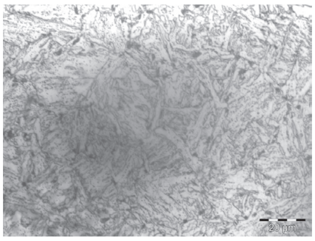
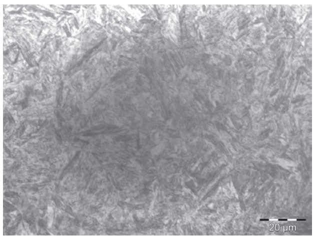
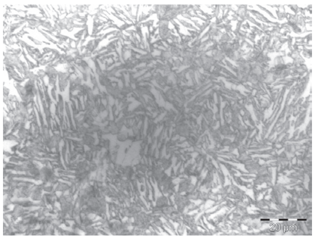
For the full annealing treatment, both steels presented a microstructure of pro-eutectoid ferrite and perlite, also presenting some regions with spheroidization linked to low temperature and cooling rate (GIRALDO ARCINIEGAS, 2017).

After the normalization heat treatment in HARDOX® 500 steel, it was possible to notice the presence of ferrite, perlite, and bainite. In relation to the normalized STRENX® 700 steel, greater homogeneity in the microstructure can also be observed. As in the case of HARDOX® 500, the microstructure was composed of ferrite, perlite and bainite, making it possible to observe in the images that the difference in the quantity of bainite is due to the carbon content and alloy elements of the materials (KONOVALOV *et al.*, 2016).

In the quenching and tempering heat treatment of HARDOX® 500 and STRENX® 700 steels, it was possible to notice that the microstructure of the samples presented themselves as tempered martensite, as well as the original, but with greater homogeneity and due to the low tempering temperature, it presents a microstructure that is very similar to the not tempered one (GORITSKII; SHNEIDEROV; GUSEVA, 2018).

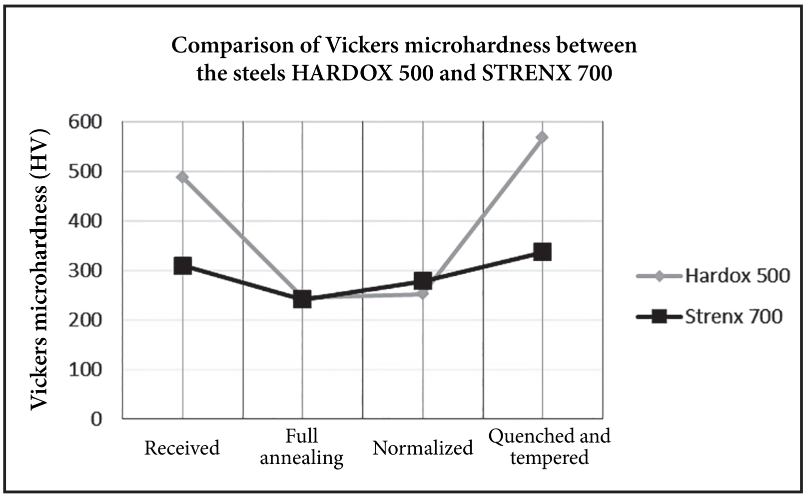
Figure 2 shows the average microhardness in the material as received, as well as the steels with their respective heat treatments.

Figure 1 – Microstructural comparison of the steels HARDOX® 500 and STRENX® 700 as received and after the different heat treatments

	HARDOX 500	**STRENX 700**
Received		
Full annealing		
Normalized		
Quenched and tempered		

Source: The authors (2019).

Figure 2 - Vickers microhardness of the steels HARDOX® 500 e STRENX® 700



Source: the authors (2019).

In both steels, it was observed that the materials received had high microhardness, what was confirmed through the microstructural examination, detecting martensite. It was also found that the hardness of HARDOX® 500 steel was greater, when compared to STRENX® 700 steel. It is also noted that HARDOX® 500 steel presented a microhardness consistent with the high mechanical resistance, staying within the microhardness range between 450 and 540 HV, guaranteed by the manufacturer (ERDEN *et al.*, 2018). Converting medium hardness to tensile strength with the aid of the ASTM standard E140 results in a strength of approximately 1620 MPa. For STRENX® 700 steel, the average microhardness, when converted to tensile strength, obtains the value of 1034 MPa above the minimum of 780 MPa required by the manufacturer. It is possible to notice that the microhardness of the STRENX® 700 has a lower value than the HARDOX® 500.

In the normalization heat treatment, there was a decrease in the microhardness of HARDOX® 500 steel, resulting in 252 HV, which, when converted to tensile strength results in a value of 847 MPa. The STRENX® 700 alloy showed a slight reduction in hardness, after treatment. It was reduced to 279 HV and approximately equivalent to a tensile strength of 931 MPa.

Both steels had the same microstructures and had a reduction in microhardness, however, STRENX® 700 steel presented a slight drop, HARDOX® 500 steel showed a great reduction in microhardness, being less than that of STRENX®, contrary to what happens with the original materials. This possibly has to do with the fact that, although the HARDOX® 500 has a higher amount of carbon, the STRENX® 700 has a higher volume of alloy elements in its chemical composition.

After the quenching and tempering treatment, the hardness of HARDOX® 500 steel increased to 568 HV, still within the expected range, but above the value of the original material, which was 488 HV. Among the possible reasons that may have caused this variation, there is a possible tempering temperature lower than the original or a possible more severe cooling speed. When microhardness is converted to tensile strength, the value of approximately 1886 MPa is obtained. With the pre-temper value reaching approximately 1978 MPa.

Verifying the decrease in microhardness, after the tempering treatment, a Vickers microhardness test was performed on a non-tempered sample and a tempered one. The values are shown in table 5.

Table 5 – Vickers microhardness of HARDOX® 500 and STRENX® 700 steels before and after tempering

Test	1	2	3	4	5	6	Average
HARDOX® 500 microhardness							
Quenched	577	610	612	596	607	575	596
Quenched and tempered	590	579	564	530	576	571	568
STRENX® 700 microhardness							
Quenched	336	367	387	371	352	332	358
Quenched and tempered	334	343	357	344	319	323	337

Source: The authors (2019).

With that, it was possible to notice that after tempering, the average hardness of the HARDOX® 500 steel decreased around 28HV and the STRENX® 700 steel decreased 21 HV. There was no great reduction being compatible to the temperature used in the tempering.

5 Conclusions

After the annealing process, it was observed that the steels had similar microstructures, with ferrite, pearlite, with slightly spheroidized microstructures. The microhardnesses of the steels were relatively close, with the HARDOX® 500 presenting a slightly higher hardness than that of STRENX® 700 and both being lower than in the normalized and in the quenched and tempered condition.

In the normalization heat treatment, the martensitic microstructure of the steels was replaced by ferrite, perlite and bainite, with an austenitic grain size 6 or finer, presenting a greater microstructural homogeneity. Both steels had the same microstructures and had a reduction in microhardness (compared to the quenched and tempered condition), however STRENX® 700 steel showed a slight drop in hardness. HARDOX® 500 steel, on the other hand, showed a greater reduction in microhardness compared to STRENX® 700. This phenomenon is associated with the fact that, although HARDOX® 500 has a greater amount of carbon, STRENX® 700 has a higher percentage of alloy elements in its composition.

Regarding the heat treatment of quenching and tempering, both steels showed an increase in hardness to the original material. The STRENX® steel showed a slight increase in hardness and the HARDOX® steel a more significant increase. The cause of this behavior is associated with a higher austenitization temperature, a more severe cooling rate, and tempering at lower temperatures. In both materials, the hardness drop was reduced after tempering. This fact is consistent with the temperature at which they were tempered. The two steels showed similar microstructures, both tempered martensite, however, HARDOX® presented a more homogeneous microstructure.

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