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Effect of induction heating on Vickers and Knoop hardness of 1045 steel heat treated

Efecto del calentamiento por inducción en la dureza Vickers y Knoop del acero 1045 tratado térmicamente

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Abstract

AISI 1045 steel is a steel of medium carbon, widely used in machinery, the automotive industry, and the food industry, among others. Therefore, to fulfill its purpose, it is necessary to improve its mechanical resistance, wear resistance and resistance to fatigue through different surface heat treatments. Variables such as heating time and hence speed affect the thickness of the hardened layer and the microstructural characteristics of the area affected by heat treatment. The inspection of the transformation of phases during the treatment and the thickness of the boundary layer is generated by determining the hardness of the material, whose procedure is subject to the ASTM E92-17 and E384-17standards, which establish the methodology to be followed. Therefore, the objective of this work is to quantify the effect of three heating times at 1123 K on the hardening of AISI 1045 steel and the regularity of the hardened layer to ensure its functionality as a component subjected to friction, in addition to developing a table of equivalences between the Knoop (HK), Vickers (HK) and Rockwell C (HRC) hardness scales.

Induction, Microhardness, Quenching

Resumen

El acero AISI 1045, es un acero de medio carbono ampliamente utilizado en maquinaria, industria automotriz, industria alimenticia, entre otras. Por lo que para cumplir con su propósito es necesario mejorar su resistencia mecánica, resistencia al desgaste y la resistencia a la fatiga mediante distintos tratamientos térmicos superficiales. Las variables, como el tiempo de calentamiento y, por ende, la velocidad afecta el espesor de la capa endurecida y las características microestructurales de la zona afectada por el tratamiento térmico. La inspección de la transformación de fases durante el tratamiento y el espesor de la capa limite se genera mediante la determinación de la dureza del material, cuyo procedimiento está supeditado al seguimiento de las normas ASTM E92-17 y E384-17, las cuales establecen la metodología a seguir. Por lo que el objetivo del presente trabajo es cuantificar el efecto de tres tiempos de calentamiento a 1123 K sobre el endurecimiento del acero AISI 1045 y la regularidad de la capa endurecida para asegurar su funcionalidad como componente sometido a fricción además de elaborar una Table de equivalencias entre las escalas de dureza Knoop (HK), Vickers (HK) y Rockwell C (HRC).

Inducción, Microdureza, Temple

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Introduction

The mechanical strength, wear resistance and fatigue resistance of medium carbon steels, such as SAE1045, can be improved by different surface heat treatments such as flame, laser and induction heating. Compared with other surface hardening methods, induction hardening shows favorable characteristics such as controlled heating depth, rapid heating, energy saving, and good reproducibility. The typical procedure for induction heating involves heating the component to the austenitizing temperature range and then rapidly cooling it until it is below the martensitic temperature (Ms). Conventional methods to determine the hardening of steels involve heating the samples in an oven for several minutes at an austenitizing temperature that depends on the carbon content of the steel [1]; according to ASTM A255, the process involves Jominy heating and tempering for the samples for 30 minutes. For steels with carbon contents above 0.37% by weight, the standard indicates an austenitizing temperature prior to hardening. The standard assumes that the steels will produce an ASTM 7 grain size. Some studies have shown an inverse relationship between austenitic grain size and hardening [2-4], which consider austenitic grain sizes in the 4-8 range.

With induction heating, the heating ratios are higher and the austenitizing times are much shorter leading to the possibility of incomplete dissolution of carbides in the austenite. Clarke et al. [5] studied the transformation kinetics of austenite and carbide dissolution in 5150 grade steels, finding that for the quenched and tempered structure all carbides were dissolved at heating rates of up to 900 ° C / s.

The time-temperature cycles that can be achieved in induction surface heating vary from one hardened part to another and depends on the initial size of the cross section and the required depth [6]. Austenitizing times can be less than 2 s and greater than 10 s depending on the part treated and the parameters of the equipment.

The main objective of this work is to examine the effects of three heating times at austenitic temperatures of 1123 K on the hardening of 1045 steel and the regularity of the hardened layer to ensure their functionality as components subjected to friction, for which they will be carried out.

Vickers and Knoop hardness tests to compare the degree of hardness at the beginning and end of the treatment; Furthermore, it is important to mention that there is controversy in the margin of error between microhardness scales such as the Vickers (HV) and the Knoop (HK), which can generate errors when converting to the Rockwell C (HRC) scale. For this reason, the methodology will be implemented to carry out the conversion between scales correctly and avoiding said error in the block & wing part manufactured by forging, which carries an induction hardening heat treatment, whose minimum hardness limit is 59 HRC and a maximum of 63 HRC; Likewise, the induction heating time on the thickness of the hardened layer will be correlated with the hardness.

Methodology to be developed

The research was carried out on SAE1045 steel pieces shown in Figure 1, due to their application, said samples must have a hardened outer layer in order to increase their resistance to wear, so they were subjected to a heat treatment of induction hardening. in a GH Induction equipment model 2X100MS150 / S. The process consists of austenitizing the material at 1123 K; For this, the equipment operating conditions were 37 kW of power at a frequency of 15 KHz, and later the pieces were cooled in a 5% polymer solution at 28 ° C, the austenitizing times were 2.0, 2.2 and 2.4 s and a total cycle of 39 s / piece. Once the pieces were tempered, they were cut transversely (Figure 1b), the evaluation points shown in the Figure. 1c correspond to the critical areas of the piece, in which hardness values greater than 50 HRC are required. The pieces were cut in a Leco MX205M metallographic cutter, with cooling during cutting to avoid heating and possible microstructural transformation of the surface.

Figure 1 Induction Hardened 1045 Steel Automotive Part
Source: Own, Solidworks

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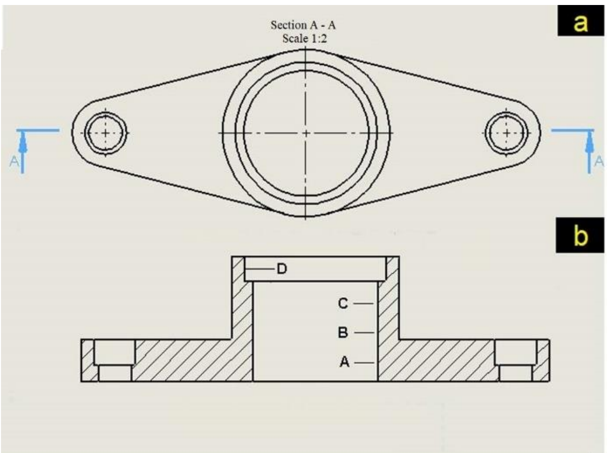

Figure 2 (a) Section studied and (b) points evaluated in the cut
Source: Own, Solidworks

After cutting, for the determination of the Vickers microhardness (HV), the samples were prepared metallographically, for this an intermediate roughing was carried out with abrasive paper of silicon carbide (SiC) grades 320, 400 and 600, then they were gave a fine slab with 800, 100, 1200 and 1500 grade abrasive paper; finally, the samples were polished with 9, 6 and 3 µm diamond paste. The microhardness tests were carried out with a Vickers Shidmazu HMV-G2 microdurometer, at a load of 0.5 kg and a load time of 10 s, 5 indentations were made per sample to obtain the statistical average and the standard deviation of the value of microhardness. The indentations were made every 100 µm in an area no greater than 1.5 mm; the foregoing in compliance with the ISO 6507-1 [7] and JIS Z2244 [8] standards, which regulate the determination of the effective depth of hardening. In addition to the microhardness tests, the Jominy curves were simulated using thermodynamic simulation software in order to predict the correlation between surface hardening and austenitic grain size.

Results

Optical microscopy of 1045 steel and nominal composition

The base material for the manufacture of the pieces is an AISI 1045 C-Mn steel whose typical composition is Fe-0.47, C-0.607, Mn-0.012, P-0.006, S-0.235, and Si-0.006, the values are given in percent by weight.

The microstructure of the analyzed AISI-1045 steel sample without heat treatment was composed of 88% pearlite (α + Fe3C) and 12% allotriomorphic ferrite (α), forming the first austenite grains. The microstructure of the material is shown in Figure 3.

Figure 3 Micrograph of the microstructure of AISI 1045 steel without heat treatment. Allotriomorphic ferrite is the light phase that describes the previous austenite grain boundaries, and pearlite is the darkest phase
Source: Own, Leco MX205M Microscope

Figure 4 shows the microstructures of the AISI-1045 steel samples heat-treated with induction heating at times of 2.0, 2.2 and 2.4 s at 1123 K, the images were acquired from the outermost area of the layer affected by the treatment. The microstructure, in the three conditions studied, showed the formation of martensite with plate and slat configurations. However, it can be observed at the lowest time studied, of 2.0 s, the presence of undissolved carbides due to the small size of austenitic grain, as has been reported in the literature (Figure 3a).

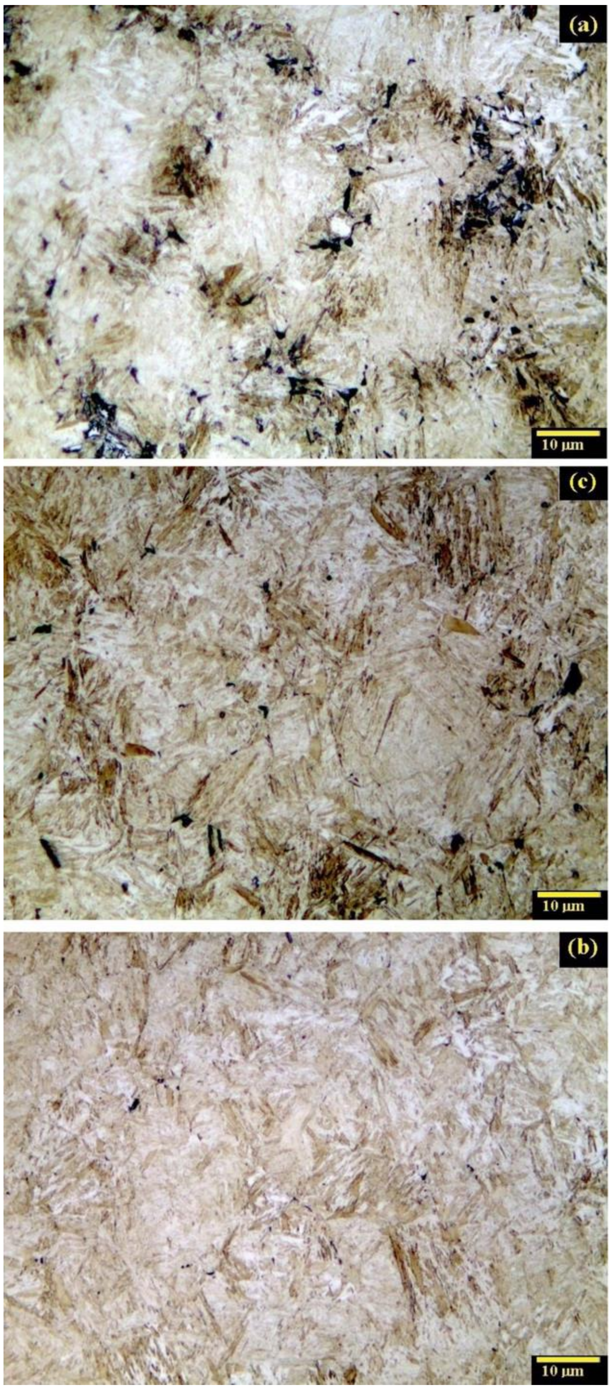

Figure 4 Optical micrographs of AISI-4045 steel samples heated by induction at a temperature of 1123 K for (a) 2.0 s, (b) 2.2 s and (c) 2.4 s and tempered in polymeric solution
Source: Own, Leco MX205M Microscope

Microhardness of the surface of hardened 1045 steel

The Vickers microhardness of the surface layer of 1045 steel subjected to induction hardening at 1123 K was found in a range of values between 709 to 744 (± 45) HV for points A, B, C and D shown in Figure 5. In general, the average microhardness values are within specification for 1045 steel treated under these conditions.

However, it is observed that at longer induction times there is an increase in hardness values, which is related to the fact that at shorter austenitic times the austenitic grain size tends to decrease due to the inverse relationship proportional to the hardness of the hardened parts. It was confirmed that short austenitizing periods generate a decrease in the hardness values for this type of steel, AISI-1045; in addition, as a function of the decrease in the austenitic grain size and the time for the dissolution of carbides during the transformation from pearlitic phase (α + Fe3C) to austenitic (γ).

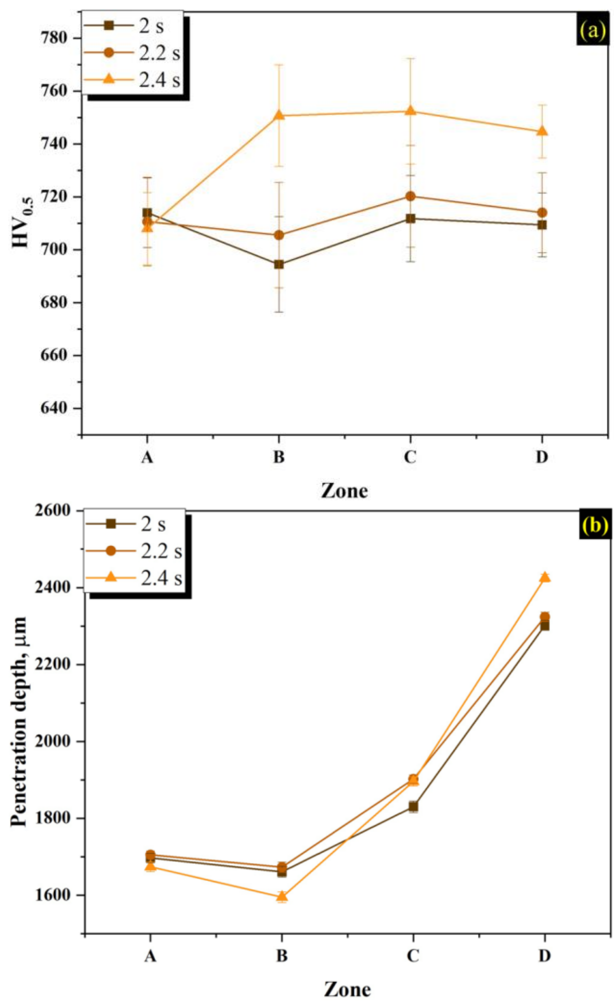

Figure 5 (a) Vickers microhardness measurements at the critical points of the automotive part indicated in Figure 1, and (b) depth of the thickness of the hardened layer in the indication quenching of AISI 1045 steel
Source: Own, Origin

HK, HV and HRC hardness equivalences

It is important to note the difficulty of converting between hardness scales, in this regard Callister [9] emphasizes that due to the fact that hardness is not a well-defined property of the material and because of the experimental differences of each technique, a general method of converting hardnesses from one scale to another.

The conversion data have been determined experimentally and found to be dependent on the type of material and the characteristics. Likewise, for the conversion between scales, data have been found for steels whose data are illustrated in Figure 6. The equivalence between one scale and another is calculated roughly by drawing a horizontal line that crosses both scales and, if necessary, performs a correlation for a more exact value of the conversion between scales.

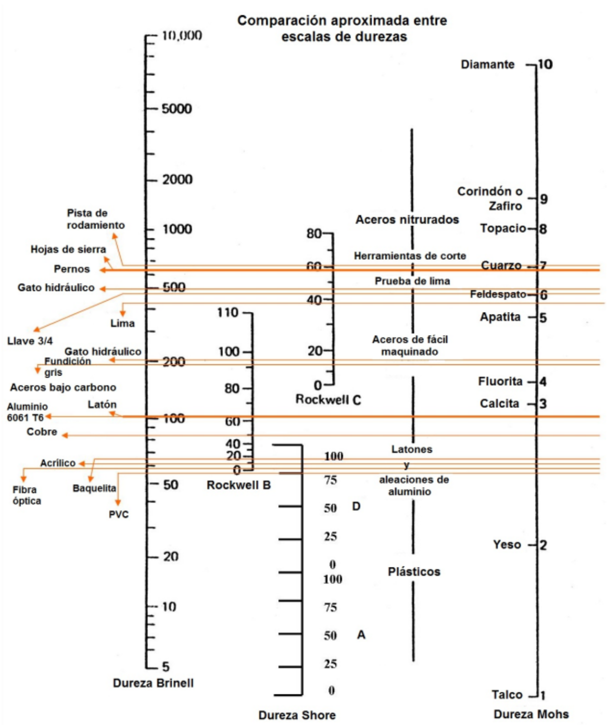

Figure 6 Schematic representation of the different hardness scales
Source: Internet

For this reason, it is necessary to establish equivalent values between the HK, HV and HRC hardness scales for AISI 1045 steel heat treated with induction heating, which is shown in Table 1. The results corroborate what was mentioned by Ghorbal *et al*. [10] where they mention that the HV / HK hardness ratio has a variation between 1.05 and 1.15. Therefore, the comparison between hardness scales should be taken with reserve; Therefore, the conversion between hardness scales is recommended only in the event that it is not possible to measure this property directly on the specified scale; Similarly, both Callister and Ghorbal *et al*. indicate that the Knoop hardness scale is more appropriate for brittle materials, so testing materials with greater ductility can generate a deviation in the hardness values determined by said scale.

Knoop hardness (HK)	Vickers hardness (HV)	Rockwell C hardness (HRC)
311	303	30
427	416	42
450	438	44
504	491	48
548	534	50
556	542	51
604	589	54
620	604	57
650	633	58
685	668	59
700	682	59
702	684	59
705	687	59
713	695	59
715	697	59
721	736	60
814	794	64
848	827	65

Table 1 Equivalences between the HK, HV and HRC hardness scales for AISI 1045 steel
Source: Own, Word

Determination of the thickness of the hardened layer

Figure 7 shows the thicknesses of the hardened layer in the four areas considered critical in the automotive part, since the surface at these points will be subjected to friction, the microhardness corresponds to large values. In the results obtained, a slight variation was observed in the measurements of the same points at the three time conditions. But, in addition, a considerable increase in the thickness of the layer was measured at points C and D. This variation was associated, not with heating by electromagnetic induction; which depends on the intensity of the magnetic field, the frequency of the working current, the separation between the piece and the inductor coil, as well as the magnetic characteristics of the material to be treated; if not to the geometric shape of the piece. In addition to the above, the austenitizing time is also a variable that influences the depth of penetration of the temper and showed a clear trend specifically at points C and D where it was observed that at austenitizing times of 2.0 and 2.2 s the thickness the layer was less; Cunningham et al. [11] indicate that the variations in the depth of the layer are due, in the case of induction by a single shot, to the exposure time of the steel above the critical temperature A3, for which it was concluded that the geometry of the piece mainly influenced the temperature reached in the different areas of the piece, and that areas A and B were exposed to a shorter time to induction heating compared to points C and D.

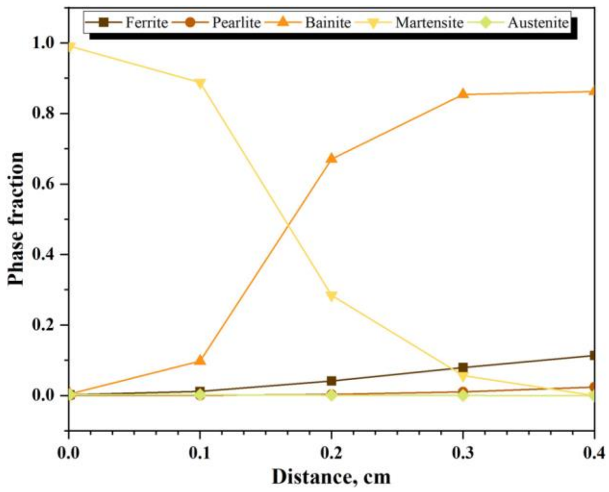

Figure 7 Phase fractions present in the Jominy test for AISI 1045 steel as a function of the penetration depth of the tempered layer
Source: Own, Origin

Figure 8 shows the results of the thermodynamic simulation with the JmatPro software, where the chemical composition of the AISI 1045 steel is considered, in addition to the ASTM grain size, whose value was determined experimentally, only for the austenitized sample for 2.4 s, and it was 9 ASTM at a temperature of 1123 K. The simulation was used in order to appreciate and confirm what was reported by Cyderman *et al*. [4], who determined that at short heating times the grain size decreases and the surface hardness of the hardened layer decreases.

The Jominy curves simulated by the thermodynamic software of Figure 8 show that with the reduction in size it generates a reduction in the hardness of the hardened layer, or in other words, the hardenability of the steel decreases with the reduction of it; this is due to the fact that a small austenitic grain size generates a greater number of precipitation centers, that is, the austenite will be less stable in austenitizing.

Stability is achieved at large grain sizes and is achieved, either by the action of temperature or time, the first condition being favorable in induction hardening, since the subjection times are short in this surface hardening technique. The results showed that in the outer layer of the material 100% of the martensitic transformation was achieved and as the distance was greater, this metastable phase gave rise to stable phases, in this case ferrite and pearlite.

Therefore, it was inferred that the hardness of the material decreased at a greater hardening depth, which was corroborated with what is shown in the simulated hardness and resistance curves of Figure 8, where it was observed that the microhardness of the material increased in the outer layer of the material, the measurement result was 684 HV at a layer depth of between 10 and 1000 µm. The above validated that the hardening capacity of the material is determined by metallurgical aspects such as the chemical composition and the austenitic grain size. It is also important to mention that the hardenability of the steel depends primarily on the carbon content, since it is fundamental for the martensitic transformation, considered as a transformation process without diffusion, in which the austenite phase distorts its face-centered cubic crystal lattice to become tetragonal.

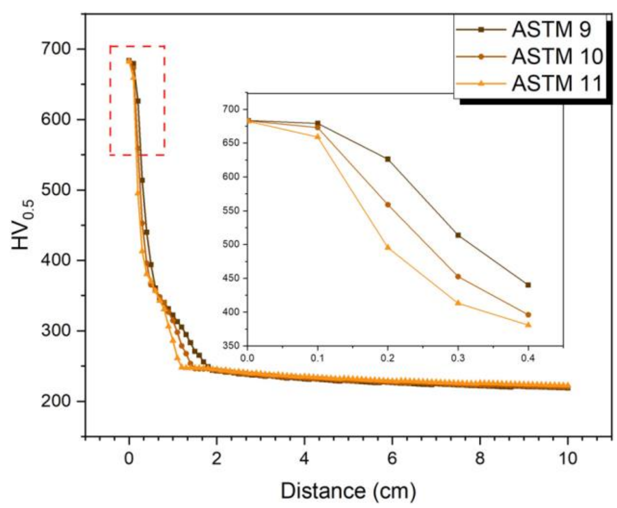

Figure 8 Simulated Jominy curves for 1045 steel as a function of austenitic grain size
Source: Own, Origin

The austenitic grain size is an important factor that determined the microstructure formed, since it influenced the phase transformation kinetics during the cooling cycle. Microstructure has been reported to have a large effect on the mechanical properties of the product, ie, it is essential to control grain size growth in heat treated alloys. Due to the above, one of the microstructural advantages of induction hardening is the refinement of the austenitic grain; the temperatures used for heating conventional Jominy specimens ensure a grain size refinement of approximately 30-40 µm (ASTM 6.5-7) [4].

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The samples with 2.4 s of austenitizing showed a grain size of approximately between 9-11 μm, so that in Figure 7 a slight influence on the hardenability of a finer grain size was observed. It is this same sense, Chongxiang *et al*. [12] studied the effect of the temperature and time variables on the growth of austenitic grain in GCr15 steel, finding that it grows gradually with temperature and holding time at different austenitic temperatures.

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Conclusions

The behavior of AISI-1045 steel subjected to a heat treatment with induction heating, was studied through the correlation of the values of microhardness (HV) and the thickness of the hardened layer at three different austenitizing times, of 2.0, 2.2 and 2.4 s at 1123 K and cooled to 301 K with a 5% polymer solution. The results of the microstructural characterization revealed that the transformation of the AISI-1045 steel, initially consisting of pearlite surrounded by allotriomorphic ferrite to martensite, occurred at the three austenitizing times tested; the final microstructure was composed of a mixture of martensite in the form of slats and plate, typical formations of steels with medium to high carbon content.

However, it was found that at a heating time of 2.0 s, the austenitizing time was not sufficient to dissolve the cementite because the grain refinement was not completed, which was verified by the presence of carbides in the microstructure of the steel treated under this condition, and that was not observed in the other times of the study. On the other hand, it was observed that at shorter austenitizing times the hardness of the layer showed a reduction in this property due to the aforementioned phenomenon of austenitic grain refinement and the incomplete dissolution of the iron carbide.

Finally, the depth of the boundary layer showed an increase in points C and D of the part that can be associated with the different exposure times to the austenitizing temperature during induction heating, mainly due to the complex geometry of the tempered part.

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