

# Isothermal Treatment at Low Temperatures Applied to AISI 4340 Steel: Effects on Hardness, Toughness and Microstructure



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**Abstract:** *The effect of the parameters of isothermal treatment at low temperatures, also called Austempering, on the impact toughness, hardness and microstructure of AISI 4340 steel was investigated. For this purpose, specimens for impact toughness tests were machined according to ASTM E 23-93a. For hardness tests, prismatic bars of 10mmx10mmx30 mm were manufactured. Austempering was performed in a salt bath furnace using 55% sodium nitrate and 45% potassium nitrate. Three temperatures: 300, 325 and 350 °C, and four soaking times: 1 min, 10 min, 1 hour and 10 hours, were used. Hardness tests were performed on Rockwell durometer and three indentations per sample on HRC scale were made. The impact toughness test was done with the Charpy method. The specimens, previously machined, were subjected to austempering, and then subjected to the respective tests. The maximum hardness value 56.75 HRC was found at 300 °C with 10 min of soaking time, and the maximum impact toughness value was 27.67 J, found under the same conditions. It was observed that the hardness and impact resistance are not always inversely related during Austempering. In all microstructure tests, a biphasic structure composed of lower bainite with lath martensite in different proportions was observed, showing that the bainitic reaction is never complete. It is concluded that when alloyed steels are subjected to the Austempering treatment, a decrease in hardness with the soaking time or variation in temperature, is not always accompanied by an increase in impact toughness, since undissolved alloyed carbides can produce embrittlement at any time and temperature interval.*

**Keywords:** *Austempering; Bainite; Hardness; impact toughness.*

## I. INTRODUCTION

The AISI 4340 is a medium carbon (0.38-0.43% C) steel, and is known in the industry to as a high strength chrome-nickel-molybdenum steel. This steel is widely used in the aeronautical industry, especially in critical applications such as landing gear, and also in the automotive industry in the manufacture of drive shafts, crankshafts, connecting rods, etc. [1]. These steels can be heat treated with high levels of

hardness, and impact toughness using various methods [2]. The Austempering treatment is one of them, and for these Steels have a wide range of industrial applications, which can replace conventional quenching-tempering treatment due to the following advantages [3], [4]: 1) They improve the mechanical properties of hardness; 2) Increase and improve the impact resistance and ductility of materials; 3) Improve resistance against subsequent embrittlement; 4) Improve the wear resistance of materials; 5) Reduce surface fissures and distortion during heat treatment. To achieve these advantages, the formation of perlite or martensite should be avoided subjecting the steel to an isothermal treatment, keeping it in a molten salt bath for a defined period of time, and then cooling it in air.

Austempering should be carried out at a temperature away from the point where perlite can form, and can be found in the bainite formation range. Two types of bainite can be produced in this process: upper bainite and lower bainite depending on the cooling rate and temperature range [5]. Both types of bainite differ in the intensity of the mentioned properties.

Austempering is an isothermal treatment, alternative to conventional quenching-tempering, during which the steel is heated to the austenitic phase and then cooled to a temperature above the start of the transformation of martensite (Ms) with the aim of getting bainite instead of martensite [6]. The reason is simple. The bainite structure, apart from its great toughness, has excellent mechanical properties [7], [8] and the brittle effect can be reduced, especially in samples of thin thickness (improves resistance and ductility) by controlling of the different phases of the matrix. In this way the pieces subjected to Austempering are left with bainitic structures, with a much higher toughness than those corresponding to identical pieces, in which the same hardness has been achieved using conventional temper-tempering. When the isothermal transformation of austenite is verified and the martensitic stage does not exist, the danger of cracks and deformations occurring disappears [9].

The upper bainite generally forms at high temperatures, while the lower bainite forms at low temperatures without reaching "Ms". This difference translates into different microstructures and mechanical properties of both the upper and lower bainite [10]. The main difference between both types of bainite is carbide precipitation. In the upper bainite, because the transformation temperature is high, the process is fast; therefore, carbon atoms do not have enough time to precipitate inside the ferrite plates.

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On the other hand, during the formation of the lower bainite, the reaction is slow because the temperature is relatively lower; and therefore, there is a greater opportunity for carbon atoms to precipitate into bainite plates or sheaves [11].

Investigations on heat treatment parameters of metals and alloys steels, have been of great interest by many researchers for many years [12], [13], but specifically on Austempering it is not as widespread.

Adewuyi and Afonja [14] and Raymond [15] define austempering as one of the isothermal treatment methods used to harden ferrous metals, greatly improving their toughness and is a better alternative to conventional quenching-tempering treatment. In general, they recommend for all ferrous materials heat the component to a temperature between: 825°C - 950°C, keep it submerged at this temperature for 1 or 2 hr, and then cool it in a hot liquid medium at a temperature between 250 °C - 450 °C, and after stirring the material, cool it to room temperature in calm air. The specific parameters and the type of bainite to obtain are determined by the chemical composition of the material.

Kazerooni et al. [16] used salt bath furnace, investigated the influence of austenitizing temperature at 950 °C, 920 °C, 870 °C, 840 °C, and 800 °C on austempering kinetics, austempered microstructure, mechanical properties and hardenability in a ductile iron alloyed with Mn-Mo-Cu. They found that by decreasing the austenitized temperature, the introduction of ferrite into the austempered structure is accelerated. Cheng-Yi Chen *et al.*, [17] studied the mechanical and microstructure properties of CrMo alloy steel (SCM 435). The heat treatment conditions of the samples were 830 °C for 15 and 25 min for austenitizing, and were immediately immersed in the salt bath furnace for Austempering. The austempering temperatures were: 290, 310 and 330 °C immersed for 30, 60 and 120 min, then cooled in water. Experimental data showed that the stability of the mechanical properties of the samples with austenitizing temperature 830 °C for 25 min were better than the samples austenitized for 15 min. Also found, that samples austenitizing at 830°C for 25 min and austempering at 290 °C, the stability of the tensile strength (UTS) was better than that of the specimens in a salt bath at 310 and 330 °C. The average hardness of all samples were over 70 HRA. The samples with austenitized at 830 °C for 25 min and salt bath at 290 °C for 30 min had the highest hardness and resistance and showed a larger grain size than the  $\gamma$ -phase austenite. The retained austenite reached 11.4% of the total volume. Thus, the austempering of SCM435 alloy was found to markedly improve tensile strength compared to the traditional oil quenching process with subsequent tempering. A. Chennakesava Reddy [18] studied the effect of temperature and holding time of Austempering on impact toughness in medium carbon and high alloy steels. It demonstrated that temperature and holding time have a great influence on impact toughness and hardness in medium carbon and high alloy steels. The austempering heat treatment produced bainitic structures. The best impact resistance values were achieved when the samples were austempered for 1 hr at 325 °C. A. A. Alabi, *et al.*, [19] studied the effect of austempering on the mechanical properties of medium carbon steels using Bitumen (fossil fuel) instead of molten salts for which using samples of 0.45% C. They found that the values for hardness, impact resistance and tensile strength increased almost linearly from the austempering time of 1 hr to 3 hr,

after which they all decreased. The maximum values of hardness, impact resistance and tensile strength were: 496.2 HV, 149 J and 706.2 Mpa achieved with an soaking time of 3 hr. Y. Ohmori, *et al.* [20] demonstrated that one of the factors that affects the toughness of Austempered structures is the size of the bundle or sheaves in which the constituents are grouped. As the number of packages increases with time, the dimensions of the Bainitic colonies decrease, presenting this bainite with a structure that is harder than Martensite due to carbide precipitation. Consequently, if the alloyed steels cause carbide precipitation during austempering in the described manner, an increase in toughness of these steels will be observed only up to a certain limit. K Irvine and F. Pickering [21], state that temperature changes in the austempering, can lead to the formation of upper, lower bainite or a mixture of both. The lower bainite at low temperatures contains finer carbide particles. Cementite is brittle and causes cracks under the influence of stresses. These factors cause the cracks to cross with the carbides or force them to spread around them, being the reason for a higher toughness of the lower bainite compared to the upper bainite.

The development of bainitic microstructure, especially lower bainite in steels, has been reported to provide a better combination of strength and toughness, but also cause loss ductility in a high volume fraction of bainite [22], [23]. Therefore, an optimal combination of mechanical properties in the elements can be obtained through the development of dual phase microstructures [24] - [27]. On the other hand, it is believed that the combination of bainite and martensite can help to obtain a better combination of mechanical properties, since bainite can induce toughness while martensite can improve hardness and mechanical resistance.

How austempering temperature and holding time affect bainite formation is well studied in plain carbon steels, but not fully studied in alloyed steels. For example, for a given temperature, an increase in holding time of alloyed steels could not always increase toughness. In some cases it may decrease, due to the role played by the alloyed carbides during the process; These can change shape or distribution generating cracks, or areas of embrittlement and decrease toughness.

The aim of this article is to study the effect of the austempering parameters (time and temperature), when the treatment is carried out at low temperatures, slightly above Ms, on the mechanical properties of hardness, impact toughness, besides analysis of microstructure obtained in the medium carbon and low alloy steel "AISI 4340".

## II. MATERIALS AND METHODS

### A. Study material.

The study material is AISI 4340 steel; It has good hardenability, toughness and resistance to fatigue. Ideal for manufacturing parts and tools exposed to traction, torsion, bending and high dynamic and mechanical stresses. In delivery condition has a hardness ~ 40 HRC. The chemical composition was found using the Atomic Absorption Spectroscopy (AAS) method. The results are observed in Table I.

**Table I. Chemical composition of AISI 4340 steel**

C	Si	Mn	Cr	Ni	Mo	S	P
0,4	0,30	0,70	0,9	1,9	0,3	0,04	0,03

**B. Samples.**

They were made from 3/4 inch thick AISI 4340 steel plates and then were machined according to the type of test. For hardness tests, prismatic bars of 10x10x30mm were manufactured, following the ASTM E18 standard. For the impact tests, the ASTM E 23 – 93<sup>a</sup> standard was followed. Three replicates per test were considered, therefore 36 samples were made (without considering metallography). For the metallographic tests, the samples were taken from the hardness specimens.

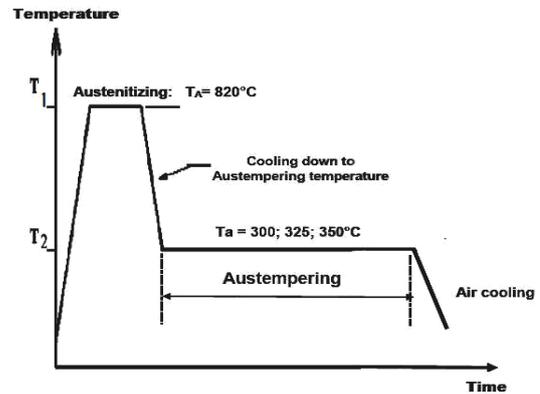
**C. Austempering treatment.**

It was carried out in a salt bath furnace. The route followed in the treatment can be seen in Figure 1. First the samples were austenitized at temperature  $T_A = 820^\circ\text{C}$ , then were cooled in a salt bath at temperatures and times austempering programmed in table II. Finally them cooled in air.

For the isothermal transformation to take place, the starting microstructure of the material must be completely austenitic. This was accomplished with the help of the Isothermal Transformation Diagram (TTT) for this stel shown in Figure 1. The austenitizing temperature  $T_A = 820^\circ\text{C}$  was selected, which guarantees a fully austenitic starting microstructure. On the other hand, the austempering being an isothermal treatment, has to guarantee the treatment temperature remains constant throughout the process. For this reason, the piece is surrounded with a molten salt bath. These salts have the property of melting at low temperatures, which means that the piece is always surrounded by liquid at the same temperature, transmitting its heat to the piece. For this purpose, a bath of sodium and potassium nitrate salts with the following composition was used: **Sodium Nitrate: 45%, potassium nitrate 55%**, with Melting point  $\sim 220^\circ\text{C}$ .

**D. Selection of treatment parameters.**

The selection of the Austempering temperature must be done by setting temperatures that are above  $M_s$ . If the TTT curve is observed for this material (Figure 2),  $M_s = 280^\circ\text{C}$ ; Therefore, temperatures and times must be used to ensure that the process, is in the bainitic transformation zone. In this sense, three temperatures have been chosen: 300, 325,  $350^\circ\text{C}$ , slightly above  $M_s$ , so that the transformation ensures the presence of lower bainite, which is the one with the highest toughness. Respect for time; it is chosen according to the degree of transformation desired. Both time and temperature must ensure that the process is within the desired transformation zone, as shown in Figure 9, and the transformation percentage can even be estimated roughly. The treatment parameters are shown in Table II.

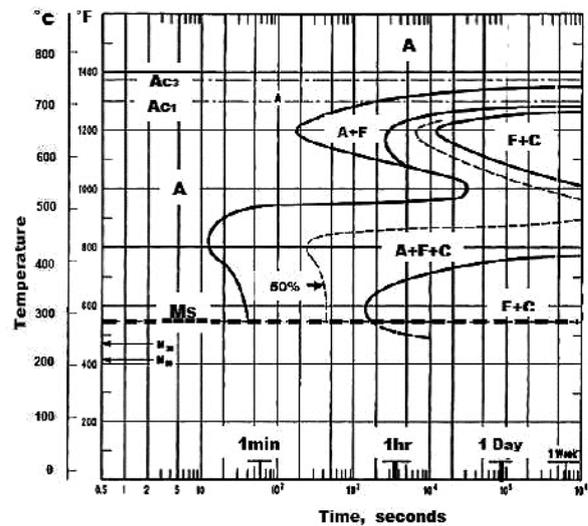


**Figure.1. Heat treatment route followed in the experiment.**

As a further check, the  $M_s$  point was validated using Nehrenberg's empirical formula [28] to estimate the  $M_s$  of the alloyed steels.

$$M_s (\text{°C}) = 500 - (300 * \%C) - (33 * \%Mn) - (22 * \%Cr) - (17 * \%Ni) - (11 * \%Si) - (11 * \%Mo) \quad (1)$$

Using the values specified in Table I and applying equation (1),  $M_s \sim 300^\circ\text{C}$  was found; empirical value that is consistent with that estimated in the TTT curve. However, the curve gives a more real value; reason why it was decided to take  $M_s = 280^\circ\text{C}$ . The subsequent results proved that it was correct.



**Figure.2. TTT isothermal transformation diagram of AISI 4340 steel, indicating with a dashed line the starting point of transformation of martensite:  $M_s = 280^\circ\text{C}$  Source: Ref. [32]**

**Tabla II. Austempering Treatment Parameters**

Temperature (°C)	Time (s) [min]
300	60 [1]
	600 [10]
	3600 [60]
	36000 [600]

325	60 [1]
	600 [10]
	3600 [60]
	36000 [600]
350	60 [1]
	600 [10]
	3600 [60]
	36000 [600]

#### E. Hardness Tests.

They were performed using the IDENTEC digital hardness tester. A preload of 150 kg with a 120° diamond cone indenter was applied, Measurements on the Rockwell C scale (Hrc) were made, and three indentations they took place for each measurement.

These tests were performed on all austempered samples, following the ASTM E18 standard, for which the samples were previously rectified and polished trying to preserve parallelism so that the reading is correct.

#### F. Impact Toughness Test.

This test was performed to measure the dynamic toughness of the samples, commonly called "Impact Resistance". These impact tests were performed on a machine "TIME Group Inc" brand and JB-S300 model, with a capacity of up to 300 Joule. The standard ASTM E23–93<sup>a</sup> was followed, suggested for small size specimens used in research laboratories. The machined specimens were then subjected to the austempering treatment and subsequently to respective impact toughness test.

#### G. Metallography Essays.

The microstructure analysis of the samples was carried out at the optical (OM) and electronic (SEM) levels. For light micrographs, a microscope Leica DMILM, 50X - 1000X was used. For the electron microscopy (SEM) the microscope used was: JEOL, Model: JSM-5600.

The specimens used were small samples taken from the specimens of hardness. To reveal the microstructure, the samples were encapsulated with polyester resin, then roughed with sandpaper, from 220 to 1000 degree with abundant water. They were polished on corduroy cloth with alumina from grade 5 μ, 3μ, 1μ, up to 0.3 μ and water for 30 sec. First, was attacked with Nital 3% for 60 sec, and then polished again in cloth, in order to remove the deformed layer due to polishing. Finally, it was attacked with Vilella reagent for 30sec, being ready to reveal the microstructure.

### III. RESULTS AND DISCUSSION

#### A. Hardness.

The results of hardness for all treatment conditions are found in Table III, from which the graphs of Figure 3 are

derived. It is observed that the austempering hardness has a decreasing trend both with the increase temperature and with the increase in soaking time. The maximum value obtained (56.57 Hrc) is presented at 300 °C, 60s (1min) and the minimum (41.87 Hrc) is at 350 ° C, 600 min (10 hr); with a significant difference of 14.7 Hrc.

It is also observed that the samples with low holding times show a minimal difference in hardness; the same happens for high times. Thus, we have for 300 °C, the samples with holding times (1 min and 10 min) show a hardness drop of ~ 1 HRC. For samples with holding times of (1 hr and 10 hr) the drop is the same ~ (1 HRC). This also happens for the other temperature levels.

The hardness results are consistent with the isothermal transformation process. Thus, for a temperature established in the transformation zone, the increase in time increases the percentage of transformed bainite until reaching the total transformation. If we observe the diagram in Fig. 2, we have that for 1 and 10 min, for the temperature intervals, the bainitic transformation does not exceed 50%, and for 60 min (1hr) and 600 min (10hr) it has occurred almost a total transformation. The results are explained by the fact that bainite is a softer phase than martensite.

Fig. 3d) shows where the conventional steel tempering curve (CR) passes. The plots show that austempering at 1 min and 10 min have higher hardnesses than those obtained by tempering. On the other hand, for samples submitted at 1hr and 10 hr, their hardnesses are lower compared to tempering. The graphs establish that the hardness of the tempered martensite can be greater or less than the (martensite + bainite) mixtures, depending on the proportion of the present phases, without considering the carbides. It should be noted that an optimal combination of mechanical properties in the elements can be obtained through the development of dual phase microstructures [25].

Fine grain size, high carbide precipitation, and high displacement density are the main factors that strengthen bainite. These factors increase when decreasing austempering temperature.

At temperatures close to Ms, the lower bainite that appear acicular form and divides the parent austenite grain, which is associated with martensite, provides a better combination of mechanical properties in AISI 4340 steel, including a suitable combination of hardness and toughness [29], much higher than that obtained by conventional quenching- tempering treatment.

The bainite obtained by isothermal transformation at very low temperatures is very hard and mechanically resistant, and can reach until high order values (60 Hrc, 2500 MPa); It also has considerable toughness and does not require mechanical processing or rapid cooling [5].

Table III. Hardness results for various time and temperature austempering conditions

Austempering Temperature (°C)	Austempering Time (min)	Hardness (Hrc)			
		Hrc1	Hrc2	Hrc3	Average
300°C	1	55,7	56,0	55,5	55,73
	10	57,2	55,7	56,8	56,57
	60	48,4	47,1	48,2	47,90
	600	47,4	47,6	46,4	47,13
325°C	1	54,7	54,4	54,5	54,53
	10	52,0	50,90	52,1	51,67
	60	45,4	45,8	45,2	45,47
	600	44,1	45,6	44,1	44,60
350°C	1	53,8	53,0	52,2	53,00
	10	52,2	52,4	52,6	52,40
	60	44,9	46,1	43,0	44,67
	600	41,8	41,9	41,9	41,87

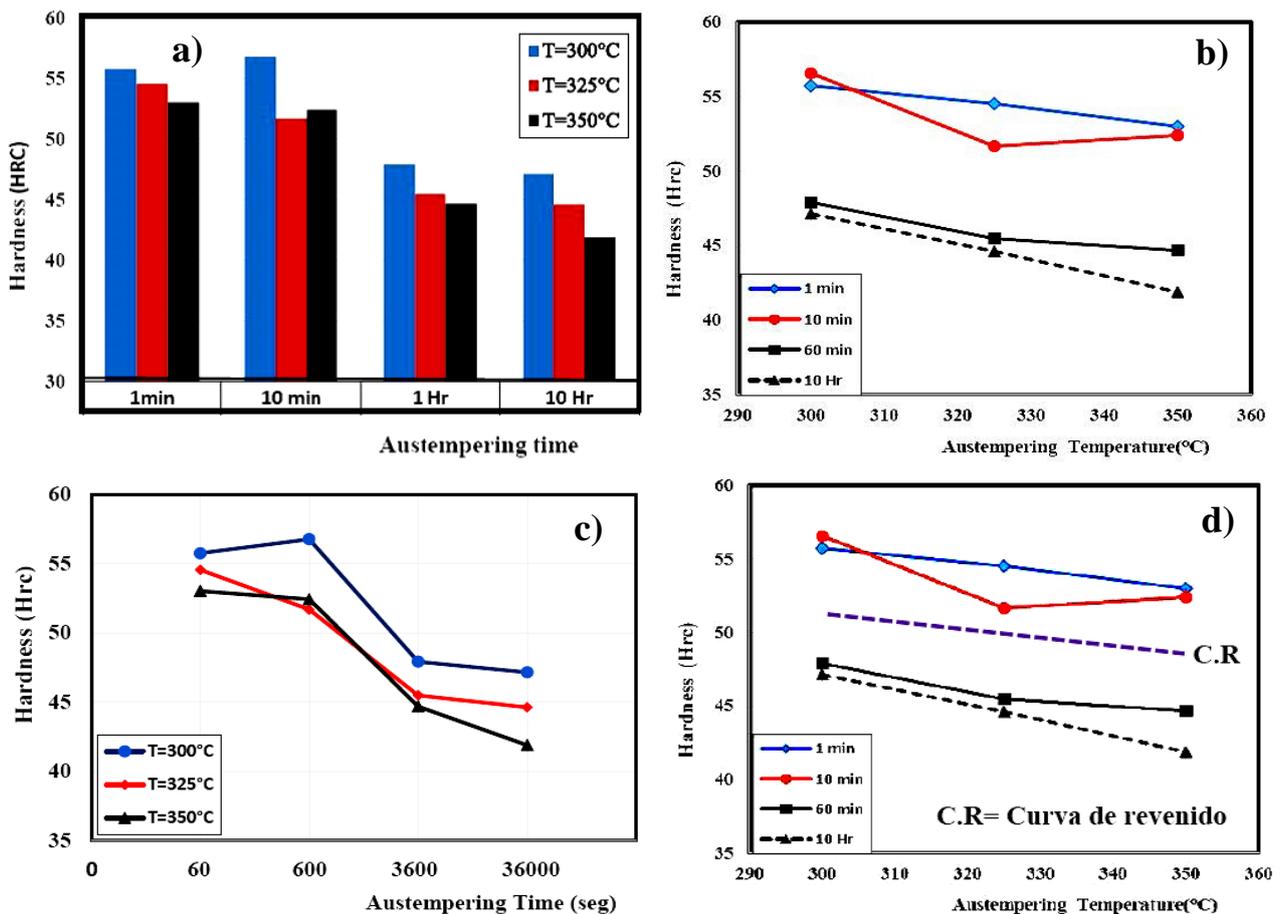


Figure 3. Graphs of hardness as a function of temperature and austempering time: a) Bar graph; b) Hardness vs. temperature; c) Hardness vs. time; d) Comparison with the hardness obtained by tempering.

**B. Charpy impact toughness.**

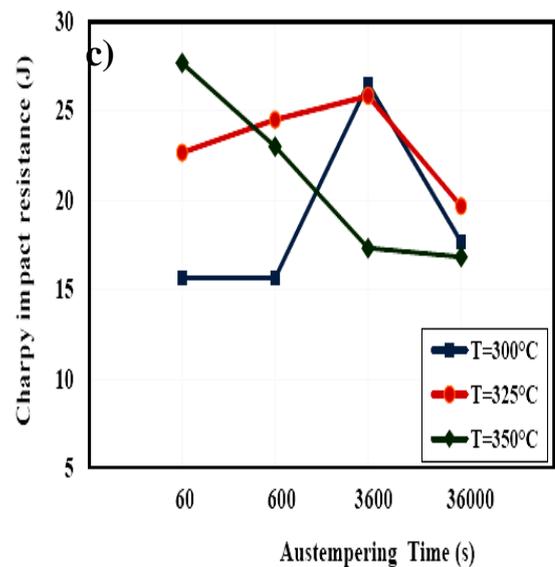
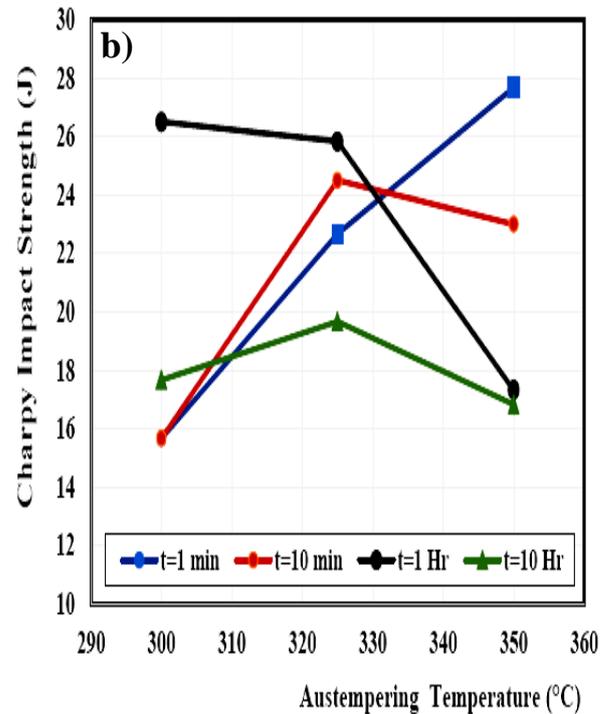
The values and variations of the Charpy impact resistance can be seen in the graphs of Figure 4. The maximum toughness value (27.67 J) is found at 350 °C; with a soaking time of 60 s (1min); and the minimum (15.67J) it appears 300

°C (1 min), having a difference of 12J due to the temperature variation. This comparison apparently reports that increasing temperature increased toughness; but later you will see that behavior is not always like this.

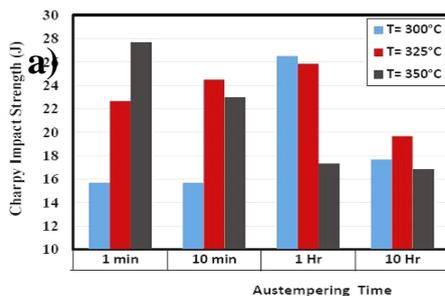
In figures 4a) and 4c), the following can be observed: For samples at 300 °C, the toughness does not vary in the interval from 1 to 10 min, but there is a notable increase in the interval (10min -1hr) until reaching 26.50J, then it undergoes a decrease in the interval (1 -10) hr, up to reaching 17.67 J. The curve is irregular with respect to temperature. For samples of 325 °C, the toughness values are increased in the interval (1min - 1 hr) and then, decrease to 19.67 J. For samples at 350 °C, the trend is totally decreasing; the decline is significant between (1 min -1 hr) and then tends to stabilize.

It can be summed up by saying: In the three temperature ranges, the toughness has not followed a uniform behavior. For some temperatures it increases and for others it decreases. These apparently contradictory results are explained as follows: In carbon steels, the tendency is always to increase toughness over times, since the bainitic transformation is not altered by the effect of the alloying elements. Bainite is a very fine scale structure of ferrite and cementite in the form of needles. In alloyed steels the important factor affecting toughness in Austempered structures is the size of the sheaves. Within the (martensite + bainite) structure, these sheaves share the same austenite grain and divide it into several sub-grains oriented in very different directions causing microcracks that dissipate a considerable amount of energy [20]. The number of sheaves increases as the holding time increases. As the number of sheaves increases, the dimensions of the bainitic colonies decrease. As a result of this: As the holding time is increased in an isothermal way, more bainite is obtained; but, this Bainite has a harder structure compared to the quenching martensite of steel. This trend of values can be justified from the works of Irvine and Pickering [21], where they express that the temperature changes in the austempering can generate the formation of upper, lower bainite or a mixture of both; and lower bainite formation at low temperatures contains finer carbide particles. What's more, cementite is brittle and cracks under the influence of stresses generate stacking of dislocations. Therefore, the increased density of dislocations and carbides in bainitic structures prevent the propagation of cracks. Those factors cause the cracks to cross with the carbides or force them to spread around them which are the reasons for the higher hardness of lower bainite compared to upper bainite.

It is considered that looking for a suitable combination of (martensite + bainite) is the important thing, since bainite provides good toughness and martensite provides high hardness besides increasing its mechanical resistance. There is no fixed rule to obtain this adequate combination. This depends on the type of steel and the treatment parameters chosen.



**Figure.4. Graphs showing the relationship between charpy impact resistance and Austempering treatment parameters: a) Bar graph: b) Impact resistance vs. Temperature c) Impact resistance vs. immersion time.**



C. Microstructure

C1. Samples: As - Quenching.

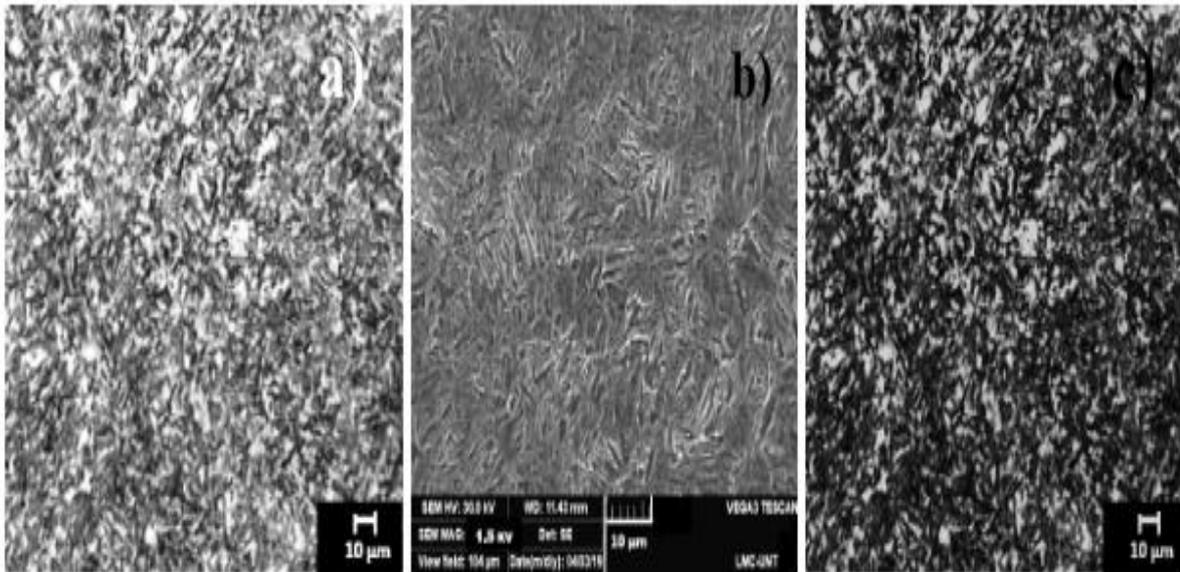


Figure 5. Microstructure of quenching samples. A pure martensite structure is observed with retained austenite zones and a large dispersion of undissolved carbides during austenitizing. a) light microscopy, b) SEM microscopy; c) dark field photomicrograph showing carbide dispersion

The microstructures of the tempered samples can be seen in Figure 5. The Figure 5a) shows the structure of the steel hardened in water. A lath martensite structure is observed, with dark spots of retained austenite and finely dispersed carbides that did not dissolve during austenitization. Figure 5b) is the same sample taken with a SEM photomicrograph. The laths of martensite that are oriented in different directions can be seen in more detail; small areas of retained austenite and small spots or dark spots that correspond to the undissolved primary carbides during austenitization are also observed.

The type of martensite is defined by the percentage of carbon in the steel. According to the graph in Figure 6 [30]. This hypoeutectoid-type steel must present a Lath-type or slat-shaped martensite morphology observed in Figures 5 a) and 5b).

Figure 5c) shows a dark field photomicrograph, where you can see the primary carbides and their dispersion within the structure. The sizes and distribution of carbides is not uniform. There are thickened carbides from 10µ to very fine carbides of nanometric sizes. The presence of undissolved primary carbides is due to the austenitizing temperature used (820 ° C) that does not reach the dissolution point of the alloyed carbides, which generally exceed 1000 ° C. For example Cr Carbide dissolves ~ 1100 ° C and W and Mo ~ 1150 ° C [31]. In all Austempering treatments these carbides will not be able to dissolve, but if they change their morphology and distribution, in such a way that they can lead to nucleation of fissures, and instead of increasing their toughness, the material would be becoming more brittle.

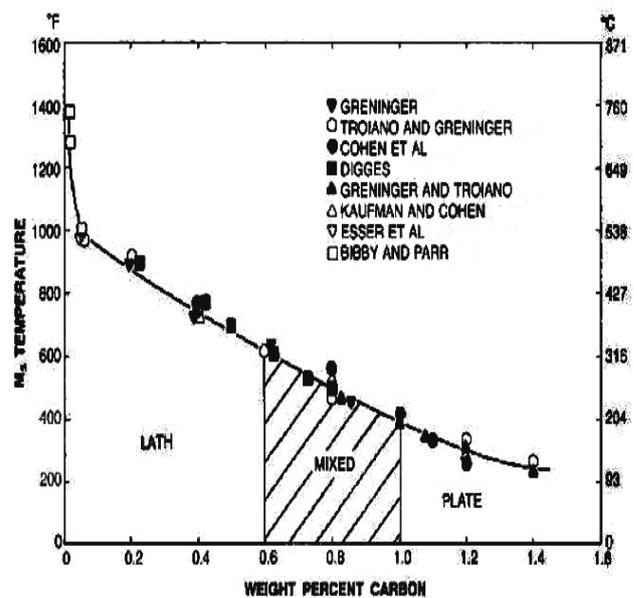


Figure 6. Temperature Ms as a function of the carbon content in steels. Composition ranges for Lath or plate martensite for steels alloys are shown. Source: Ref. [30]

C2. Austempering Samples

The microstructures of the most representative samples have been selected, to be analyzed both at the optical (OM) and electronic (SEM) levels. In Fig. 7, there are three samples austempered at 300 °C and 350 °C observed at the optical level. Comparing the tempered microstructures of Fig. 5 and the austempered microstructures of Fig 7, in the latter, the presence of the new “bainite” phase is observed, together with a fine-grained structure in size along with a dispersion of carbides. Due to the temperature level, it's about lower bainite, which at very low temperatures close to Ms is confused with the martensite structure.

A) Optical microscopies (OM)

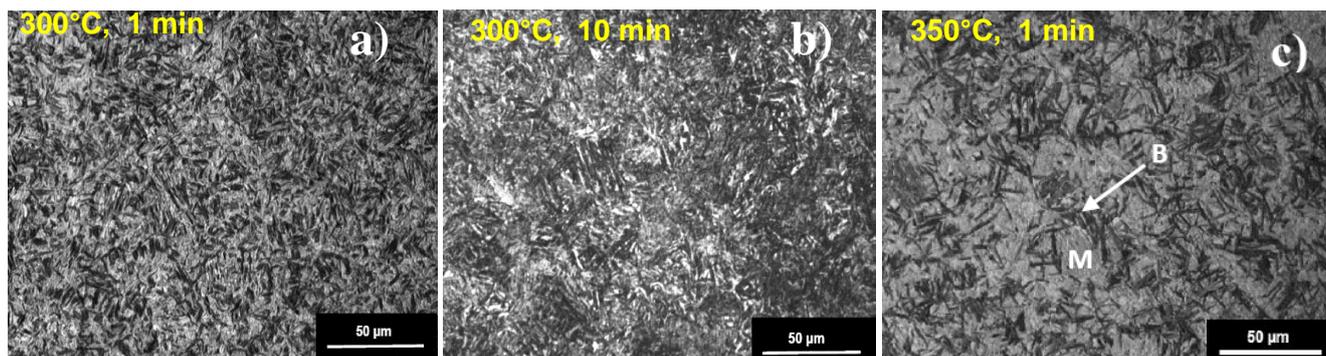


Figure 7. Optical microphotographs (OM), showing on the same scale the microstructures of some samples obtained with the austempering process executed at different temperatures and soaking; B: bainite, M: martensite.

B) Electron Microscopies (SEM)

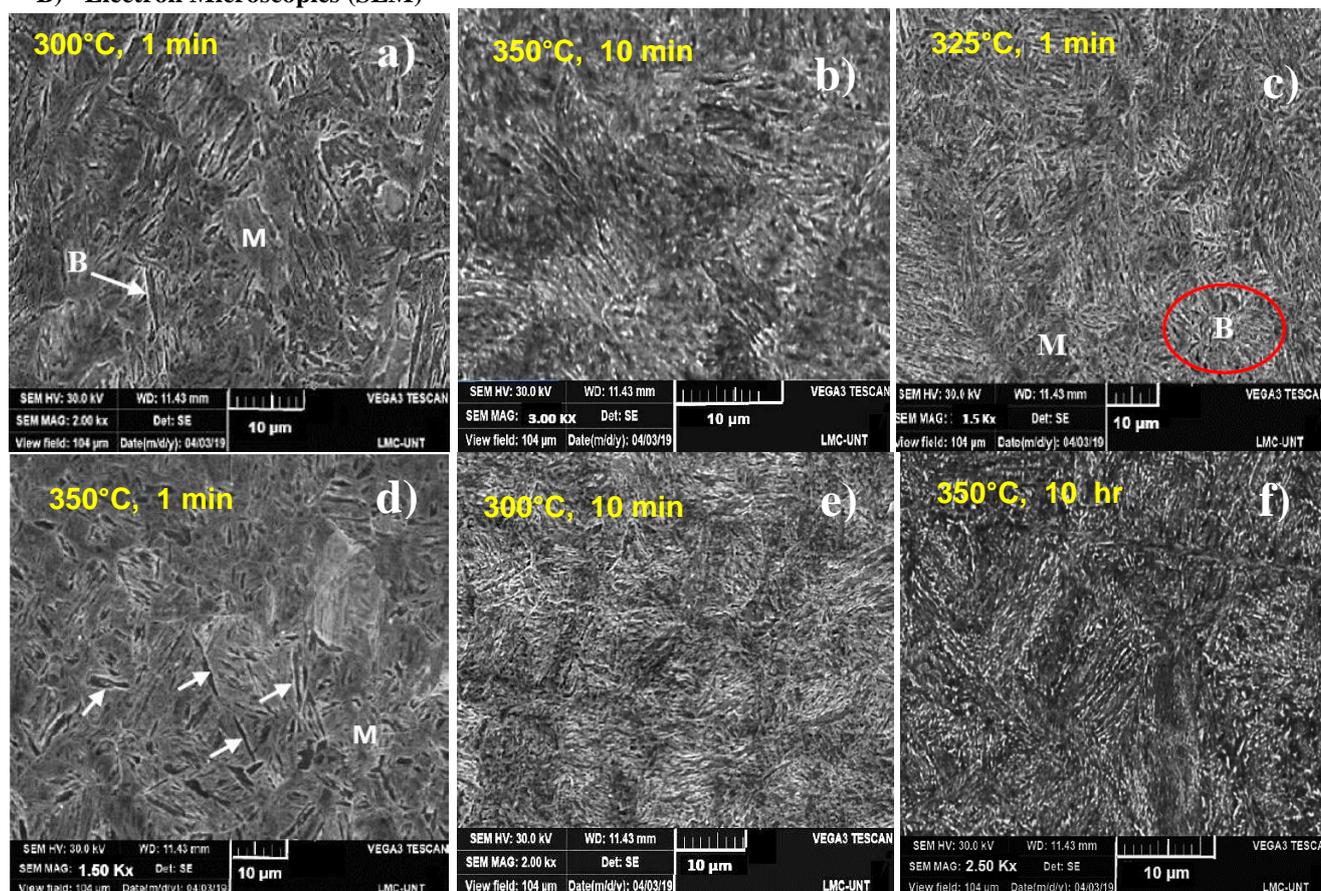


Figure 8. SEM micrographs taken at different scales showing the microstructures obtained with the austempering process carried out at different temperatures and residence times. In all samples there is a combined structure of martensite plus bainite in different proportions. The white arrows indicate the bainite sheaves that are forming. From figures a) to figure e), the combination of martensite plus bainite is clearly seen. In figure f) due to the excessive soaking time submitted after the transformation, the structure has been deformed. In this last figure, a large precipitation of secondary carbides is observed.

In Fig. 7c) the biphasic structure (M + B) can be seen more clearly. This is observed when the transformation is not complete. Also, This can also be noticed at slightly higher temperatures, because when the temperature is close to  $M_s$  bainite is often confused with martensite.

Fig. 8a) show the isothermal transformation of the samples subjected to 300 °C for 1 min. Both bainitic and martensitic structures are revealed. Long bainite sheaves are observed. Also show a structure with a large amount of martensite due

to the short soaking time. This structure justifies the high hardness values due to the high volume of martensite.

Fig. 8e) shows the structure samples obtained after being treated at 300 °C for 10 minutes. The product seen, is partially bainitic and partially martensitic. Bainite sheaves grow parallel to each other and appear as long loops, both light and dark. Martensite is also formed because the sample is quenching after 10 minutes.

The only difference from the previous one, is that the microstructure thickens and the parallel arrangement of sheaves leads to a non-parallel structure. The results show that there is not much difference between the hardness and impact toughness between the samples at 300 ° C subjected to 1 minute and 10 minutes. The other hand, the highest and lowest hardness values are between these two levels, which means that in these structures, the amount of bainite is less than the amount of martensite.

Fig. 8c) shows a mixed structure of bainite and martensite, which is obtained after austempering at 325 ° C for 1 minute. The image clearly shows the presence of the lower bainite sheaves. Martensitic structures are also present and distinguishable. The impact resistance values are much higher compared than those obtained at 300 ° C for 1 minute due to the presence of higher amounts of bainite. The effect of temperature also makes itself felt.

Fig 8d) shows the structure obtained at 350 ° C after 1 minute of holding, consisting of a mixed structure of bainite and martensite. The results of mechanical tests for these conditions are conclusive, since the structure contains the largest amount of bainite compared to its counterparts at 300 ° C and 325 ° C. The bainitic structures observable in the images give evidence of this fact. Likewise, the fact that this sample at this temperature and time has the highest toughness with the minimum hardness, as can be seen in Figures 3 and 4, gives reason for the fact, since at these conditions the kinetics of Bainite reaction provides a higher rate of formation of this phase.

Fig. 8f), shows the structure obtained after being treated at 300 ° C for 10 hr. If the TTT diagram is observed, the total transformation is achieved after ~ 1hr. By keeping it 10 hr the structure has undergone a diffusion process that gives rise to a completely deformed bainite.

For a better understanding and visualization; The locations of the transformations are shown in Figure 9 according to the reduced TTT Diagram of Figure 2 corresponding to AISI 4340 steel. Thus we have that Figure 8a) corresponds to the red point that is very close to the martensitic transformation line Ms, with little time from the beginning of the transformation, which is why large grains of nartensite are observed with narrow, small and elongated sheaves of bainite y alargadas gavillas de bainita.

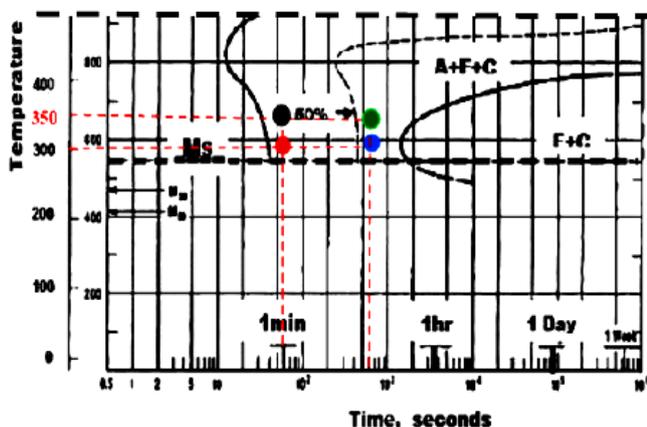


Figure 9. Diagrama TTT de transformación isotermica recortado (Fig. 2) del acero AISI 4340. Se muestra la ubicación por puntos de algunas imágenes presentadas:

**Punto rojo y azul: transformaciones a 300°C, con 1 y 10 min respectivamente; Punto negro y verde: transformaciones a 350°C, con 1 y 10 min.**

Figure 8e) corresponds to blue point, where it is observed that 50% of the transformation has been slightly exceeded. Therefore, it can be say that for samples austempered at 300 ° C with 10 min of transformation, a mixture of martensite plus bainite is obtained in almost equal percentages, keeping coherence with the microphotography.

Figure 8d) corresponds to the black point. Although it has the same time as sample 8a), the structures are different because depends not only on the increase in temperature, but also on the net time in which the transformation has occurred, since this point is much farther from the curve of the transformation, that is, there has been a longer incubation time for the start of transformation, and more bainite has been produced, reducing the amount of martensite.

Figure 8b), corresponds to the green point, which is the sample obtained at 300 ° C with 10 min, it is also observed that the net transformation time is longer and must have a higher amount of bainite. The notorious difference in morphology is apparent, due to the higher magnifications in which the microphotography was taken.

#### IV. CONCLUSION

From the study of AISI 4340 Steel treatments at low temperatures and their effects on hardness, toughness and microstructure, it can be summarized their conclusions in the following points:

1. Hardness decreases as the time and temperature of isothermal transformation increases. The maximum value 56.75 Hrc was obtained at 300 ° C with 10 min of holding, which represents an increase of 16.75 Hrc with respect to the initial value (40 Hrc).
2. Impact toughness increases as temperature increases, but this happened for low holding times (1min - 10min) without passing 50% transformation. For longer times, an oscillating trend was observed. The maximum value obtained was 27.67 J found at 350 ° C for 1 min.
3. In all tests, structures composed of lower bainite and martensite were found in various proportions, including points that were beyond the final transformation curve; which shows that the Bainitic reaction is never entirely complete.
4. Samples with the same transformation percentages have been observed, which does not imply that the properties are the same. These are directly related to the time and temperature parameters.
5. Good stability in primary carbides has been observed in all tests. However, due to diffusion, the process has produced alloyed secondary carbides, creating agglomeration zones, which explains the oscillating behavior of toughness.
6. It is concluded that the increase in austempering time and temperature produces a decrease in hardness; but this decrease in hardness is not always accompanied by an increase in impact toughness. Situation different from simple carbon steels, wich make the effect of alloying elements be notorious and the way in which alloyed carbides change the trend.

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