Toughness enhancement of low carbon steel through bainitic transformation

Aumento de la tenacidad del acero bajo carbono mediante transformación bainítica

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***Abstract*— This study investigates the effect of continuous cooling treatment on the impact toughness and ductile-brittle transition temperature of a low carbon ferrite-pearlite dual-phase steel. Impact testing was performed according to ASTM E23 at temperatures ranging from -60ºC to 90ºC. The results indicate a significant increase in toughness of approximately 64% and a reduction in the ductile-brittle transition temperature from 50ºC in the as-received condition to 0ºC after heat treatment. These changes were analyzed through microstructural examination and fractographic analysis. A bainitic transformation was observed, leading to microstructural refinement and an associated toughness improvement. Additionally, a change in fracture surface morphology was noted in the heat-treated steel, as the bainitic transformation resulted in an increased ductile fracture area across the tested temperature range.**

***Index Terms*— Toughness, Charpy impact test, dual-phase steel, bainitic transformation.**

***Resumen*— Este artículo estudia el efecto sobre la resistencia al impacto y la temperatura de transición dúctil-frágil del tratamiento de enfriamiento continuo para un acero de fase dual de ferrita-perlita con bajo contenido de carbono. El ensayo de impacto se ejecutó de acuerdo con ASTM E23 a una temperatura entre -60ºC a 90ºC. Hubo un aumento en la tenacidad de aproximadamente el 64%, y una disminución en la temperatura de transición dúctil-frágil de 50ºC (acero estado entrega) a 0ºC después del tratamiento térmico. Los cambios obtenidos se analizaron a partir de la microestructura y las superficies de fractura del material. Se evidenció una transformación bainítica que permitió un refinamiento microestructural y, en consecuencia, aumentó la tenacidad.**

***Palabras claves*— Tenacidad, ensayo de impacto Charpy, acero de fase dual, transformación bainítica.**

I. INTRODUCTION

The amount of energy required to fracture the material and the ductile-brittle transition temperature (DBTT), the temperature at which the material changes its behavior from ductile to brittle, are properties of great importance for purposes of engineering design, which can be evaluated with impact tests. The type of material behavior is evidenced on the fracture surface: on the one hand, a granular, shiny, and relatively flat surface appearance indicates a brittle material, and the on the other hand, a dull, porous appearance, with some stretch marks, shows a ductile material. [1-3]. Fracture avoidance in vessels and pipelines is an important engineering challenge because they are usually subjected to low temperatures and could enter in the DBTT of the material [4]. If this condition is disregarded in design, a brittle fracture may occur. Brittle fracture is defined as the sudden rapid fracture under stress, where the material exhibits little or no evidence of ductility [5]. This fracture is unexpected and catastrophic since it can propagate at high velocity [6]. Moreover, not only vessels and pipelines may suffer low-temperature embrittlement [6], but also the aerospace, nautical, nuclear and fossil-fuel power generation, chemical and other industries suffer as well [7].

Heat treatments in steels allow obtaining a wide diversity of mechanical properties in the material, without altering the carbon content or alloy elements. The toughness in steels can be enhanced by heat treatments of annealing (or tempering after quenching), allowing internal stress relief, increase in grain size, homogenization in the microstructure, nucleation of new grains (in case of a previous material deformation), and other mechanisms [1].

Due to the rapid cooling in the quenching treatment, there is not enough time for the atoms in the steel arranged in an FCC (austenite) crystalline structure to transform into a stable phase BCC (ferrite). Annealing allows the atoms in the steel to be located more stably from the metastable phase (generated by continuous cooling), thus enabling stress relief, precipitation in the matrix, formation of phases such as ferrite, and other mechanisms, according to the treatment temperature and time.

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Since the presence of single-phase ferrite is greater in the microstructure of the material, the energy absorption capacity increases [8], and a lower amount of high hardness phases allows an increase in material toughness [9,10]. The variation in mechanical behavior obtained by heat treatments can be evidenced and explained by a microstructural study.

Due to their high strength, toughness, and weldability replacing the conventional quenched and tempered medium-carbon steels, low-carbon bainitic steels have created enormous interest among scientists across the world [11]. Bainitic steels are regarded as relatively new steels because not long ago it was impossible to produce them in the industry with the required strength and toughness [12]. Toughness in bainitic steels is directly related to the volume fraction of bainite and fine grain size reached in the microstructure [11-13]. According to the API grade, toughness is better in bainitic than ferrite-pearlitic steels [14]. Specifically, within the bainite formation, the mechanical stability of retained austenite is important to obtain good toughness in bainitic steels [13,15]. Carbide free bainite has achieved the highest strength and toughness combinations to date for bainitic steels in as-rolled conditions [13].

Several works indicate the effect of annealed treatment on the value of the impact toughness and DBTT in dual-phase steel, increasing the amount of energy required to fracture the material at low temperatures and also reducing the DBTT [16,17]. Nevertheless, research to enhance toughness in steels by bainitic transformation is limited. This study aims to determine the relationship between the energy absorbing capacity at a wide range of temperatures and microstructural characteristics modified by continuous cooling heat treatment in low carbon steel.

II. Materials and Methods

When A low-carbon steel (AISI 1020) with extensive industrial and structural applications was selected. As-received material was provided in a cold-rolled condition. Chemical composition, determined by optical emission spectrometry, is shown in Table I.

TABLE I
CHEMICAL COMPOSITION OF THE DUAL-PHASE STEEL.

Element	wt%
C	0.174
Si	0.156
Mn	0.788
P	0.022
S	0.012
Cr	0.010
Ni	0.036
Mo	0.012
Fe	98.67

Source: The authors

The heat treatment for steel samples included austenitizing at 840ºC for 30 minutes, continuous cooling in unshaken water, and then annealing at 650ºC for 40 minutes followed by air-cooling. In both cases, continuous cooling and annealing treatment, the furnace was preheated to avoid excessive decarburization.

The Charpy impact test was executed according to ASTM E23-24 [18]. A Charpy impact machine, WPM Veb Toffprufmachinen brand, with a capacity of 30 Kg-m (294.3 J) was used. The dimensions of the samples were 10 mm x 10 mm x 55 mm with a V-notch at 45º and 2 mm deep. The test was carried out at a temperature between -60ºC to 90ºC to determine the ductile-brittle transition temperature. Alcohol with liquid nitrogen was used to cool the samples, and hot water to heat them. Samples and centering tongs were stabilized at a set temperature for 5 minutes. The test time per sample was lower than 5 seconds.

Optical micrographs were analyzed using a Leco optical microscope, and a Tescan Vega3 scanning electron microscope (SEM). The fracture surface was analyzed using an Olympus stereoscope and the SEM microscope previously used.

III. Results and discussion

A. Microstructure

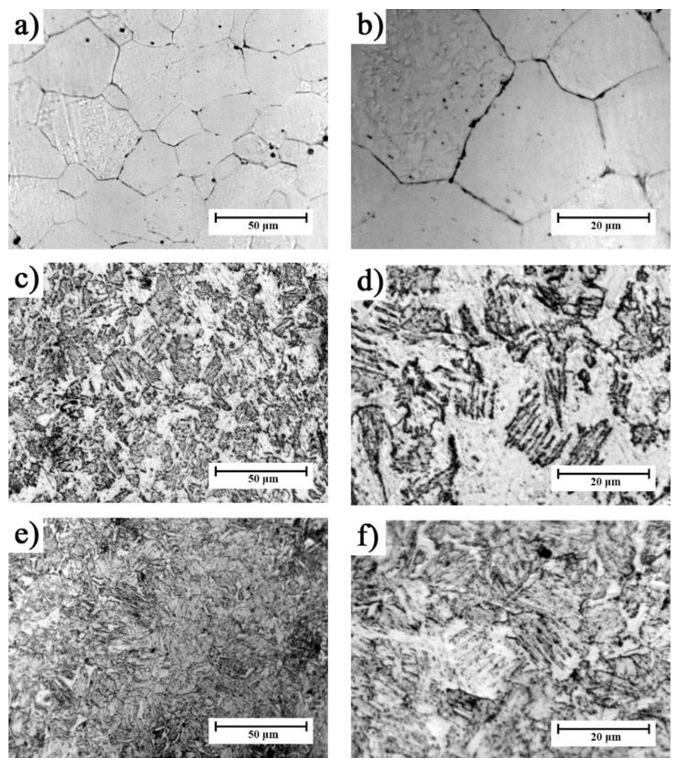

Figure 1. Optical micrographs of as-received steel (a, b) and heat-treated steel on the surface (c, d) and the center (e, f) of the sample. Source: The authors

Fig. 1 shows optical micrographs of as-received steel. Ferrite grains for low carbon steel (Fig. 1a and 1b) are evidenced, with a grain size ASTM 7-8 approximately [19]. The microstructure obtained by heat treatment is evidenced on the surface (Fig. 1c and 1d) and in the center of the material (Fig. 1e and 1f). The presence of two phases is evident in both cases. The white phase corresponds to the formation of ferrite; however, it is possible to observe some very fine precipitates within this phase, possibly due to carbides formation. Between the surface and the center of the material, an increase in the white phase (ferritic matrix) is observed, corresponding to a process of decarburization of the steel during heat treatment. The dark phase does not allow a clear identification with this magnification; in some regions, short, acicular, and/or granular precipitates are observed. Very thin and no uniform elongated plates are also observed forming linear or islands clusters. The morphology is not clear and very diffuse in other areas. The dark phase regions are more diffuse and thinner in the center of the material, thus making it difficult to identify the microstructure.

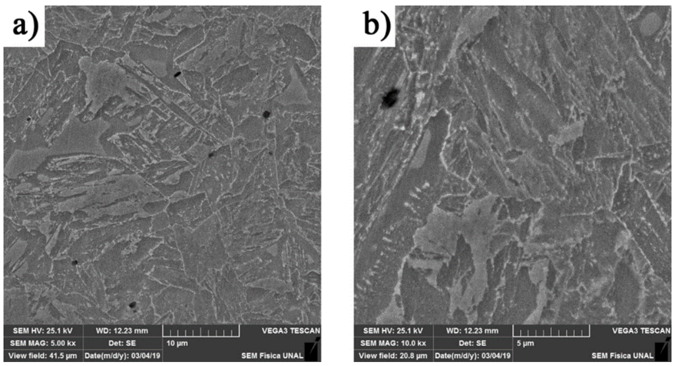

Figure 2. SEM micrographs of heat-treated steel in (a) medium and (b) high magnification. Source: The authors

Fig. 2 shows the microstructure of heat-treated steel obtained by SEM in different scales. A low-relief ferritic matrix is conserved, with some precipitates in greater relief, thus presenting an acicular and/or granular morphology in most regions, arranged in a linear distribution in some cases, and more dispersed in others. A notable difference of sizes is observed between these precipitates, with some of them being still very fine to achieve a clear identification. Similar SEM micrographs to Fig. 2 were reported by Vander in bainitic steel [20] and Bhadeshia in 0,15C-2,25Cr-0,5Mo wt% steel [15]. According to the observations made above, and to comparisons with some references, it is determined that the microstructure corresponds mostly to granular bainite, due to the continuous cooling treatment. References pointed out a granular bainite microstructure with some regions of retained austenite and tempered martensite [15,20,21]. Additional phases could be part of the microstructure obtained in this study.

The formation of bainite by continuous cooling treatment can be explained due to the overlapping of characteristic C-curves for the formation of pearlite and bainite in TTT transformation diagrams. For steels where the reaction rate is rapid, it becomes experimentally difficult to distinguish the two C-curves as separate entities [15,22]. For plain carbon and very low-alloy steels, a significant overlap is observed between the transformation temperature ranges of bainite and pearlite [20,23], taking the form of just a single C-curve. Since the different reactions overlap, it is difficult to distinguish the curves using conventional experimental techniques [15]. However, Bhadeshia [23] has proposed mathematical models based on thermodynamic analyses of isothermal transformations for the prediction of TTT diagrams in an extensive range of steels. In this C-curves perlitic and bainitic transformations are distinguished and compared with experimental results.

Fig. 3 shows the specific CCT (continuous cooling transformation) diagram for the chemical composition in table I. In addition to the initiation ferritic transformation line, the Bainitic transformation line is highlighted between cooling rates of 0,16 to 40 C/s. Vander Voort, G. [24] presents a small region of bainitic transformation CCT diagram for an AISI 1010 steel. Granular bainite is only observed in low- or medium-carbon steels and associated with continuous cooling processes rather than isothermal treatments [15,20]. Because the transformation occurs gradually during cooling, the bainitic packets are coarse, giving the resultant microstructure a granular appearance [20]. A characteristic feature (yet not unique) of granular bainite is the lack of carbides in the microstructure because the carbon partitioned from the bainitic ferrite stabilizes the residual austenite; this typically results in bainite, retained austenite, and some high-carbon martensite being present in the microstructure [15,20]. The low carbon concentration ensures that any film of austenite or regions of carbide that might exist between sub-units of bainite is minimal, making the identification of individual platelets within the packets rather difficult using optical microscopy [15]. In general, the peculiar morphology is a consequence of two factors: continuous cooling transformation and low carbon concentration [15].

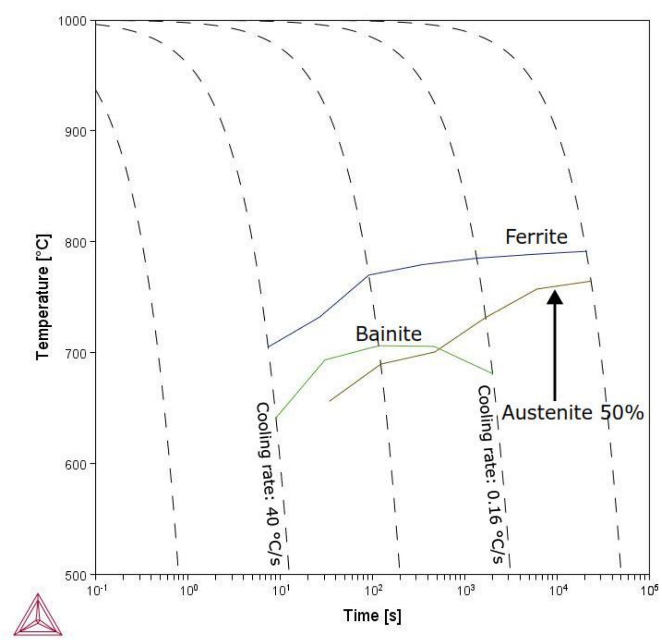

Figure 3. Thermo-Calc continuous cooling transformation (CCT) diagram analysis. Source: The authors

B. *Impact test (DBTT and energy absorption capacity)*

Table II summarizes the impact toughness results for all the temperatures analyzed and the applied sigmoid fitting function. Fig. 4 shows the energy absorbed by impact test. Behavior is observed for as-received and heat-treated steel, both curves represent a sigmoidal function. For as-received steel, a brittle behavior is exhibited below 20ºC, and it is presented with a completely ductile fracture above 80ºC approximately. This range corresponds to the transition temperature of the ductile-brittle behavior of the material. The temperature corresponding to the average energy between the ductile and brittle regions was selected as a criterion (within several applicable criteria) to determine the DBTT [2]. Therefore, it is estimated in the middle region, corresponding to 50ºC as the transition temperature of the material.

TABLE II
CHARPY IMPACT ENERGY TEST FOR AS-RECEIVED AND HEAT-TREATED STEEL.

Temperature (°C)	Energy absorbed (J)	Standard Deviation (J)	Sigmoid Funtion (J)
As-received			
-60,0	1,67	1,36	8,26
-49,8	4,09	1,15	8,26
-40,0	4,09	0,91	8,26
-20,0	3,47	0,85	8,26
-10,0	7,32	0,98	8,28
0,0	10,14	3,12	8,34
10,0	10,43	1,53	8,54
22,8	17,99	2,87	9,72
30,8	21,35	2,68	12,22
40,0	26,23	2,36	19,92
50,0	28,87	10,44	39,01
60,0	63,04	24,20	64,30
70,0	97,09	7,65	80,74
80,0	77,92	7,43	87,12
92,4	86,82	5,16	89,28
Heat-treated			
-60,0	28,63	1,39	8,26
-31,0	71,42	26,35	8,26
0,0	91,72	0,00	8,26
21,1	159,58	29,70	8,26
30,0	139,30	6,94	8,28
40,0	154,95	25,44	8,34
50,0	141,02	20,02	8,54
60,0	139,06	2,71	9,72
93,0	150,88	5,55	12,22

Source: The authors

For heat-treated steel, a fully brittle behavior is exhibited below -30ºC approximately, and the same way, it exhibits ductile behavior above 20ºC. According to the selected criterion, the transition temperature of the heat-treated steel is determined between 0°C and 5ºC approximately. A notable change in DBTT and energy absorption capacity by the steel after heat treatment is observed.

Transition temperature range for both cases have a similar size. However, there is a decrease of between 40ºC and 50ºC in the value of the DBTT after heat treatment, indicating that the steel has a higher ductile behavior, in a higher region of temperatures than as-received steel. Moreover, a considerable scattering in the DBTT region is observed in both cases, showing more notable in the heat-treated steel. This behavior was also described by Shi et al. in 0,09C-1,33Mn-0,13Mo-0,34Ni wt% steel [4] and Cubides in 0,18C wt% steel [25].

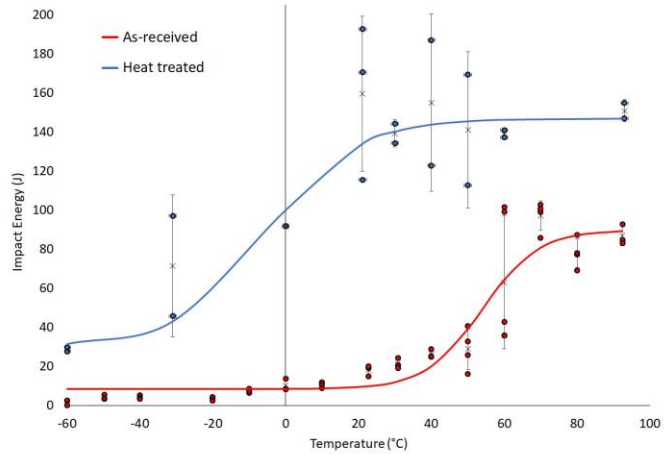

Figure 4. Energy absorbed in Charpy impact test at different temperatures for as-received (red) and heat-treated steel (blue). Source: The authors

The upper shelf energy by the as-received steel is 97 J at 70ºC approximately. For heat-treated steel, upper shelf energy is 159 J at ambient temperature (22ºC) approximately. Therefore, after the heat treatment, there is an increase in material toughness of 62 J approximately in energy absorbed by the impact, corresponding to an additional 64% respect to the as-received steel. Similar results have also been reported by Ibrahim in 0,18C-0,66Ni-0,58Mo wt% steel obtaining an increase in energy absorption capacity of steel from 80 J to 200 J and reduced DBTT from 25ºC to -25ºC, after continuous cooling and annealed treatment [26].

This behavior obtained can be explained due to bainitic formation, which causes a deviation in the crack propagation path enhancing impact toughness and decreasing its transition temperature [17]. The impact toughness and its scattering could be determined by the bainitic packet's size and its distribution. [4].

C. *Fracture*

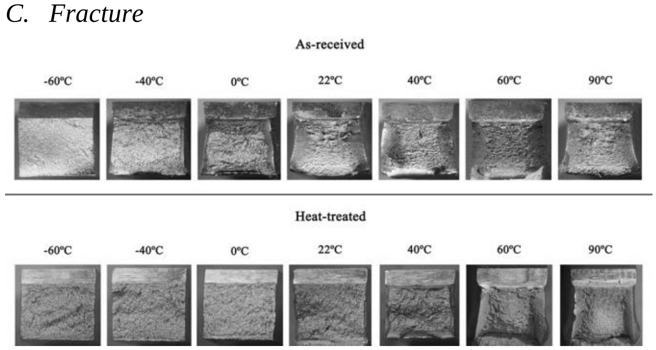

Figure 5. Fracture surface after the Charpy impact test at different temperatures of as-received and heat-treated steel.Source: The authors

Fig. 5 shows photographs of the fracture surface. For as-received steel, a completely brittle fracture is observed below 0°C, with a percent shear fracture of 0% (value calculated according to the fracture appearance procedure mentioned in ASTM E23 [18]). At room temperature (22°C), a brittle behavior is conserved; however, an increase in the percent shear fracture of 10% is observed. At 40°C, the percent shear fracture increases to 30%, showing a combined behavior. At 60°C, there is a predominantly ductile fracture, with a percent shear fracture of 85%. According to the criterion used, it is determined that the temperatures of 40°C and 60°C belong to the ductile-brittle transition region of the material. At 90°C, it presents a percent shear fracture of 100%, therefore, at higher temperatures, the material will have a ductile behavior.

For heat-treated steel, a brittle fracture is shown at -60°C and -40°C, presenting a small variation in the percent shear fracture, taking values of 0% and 10% respectively. However, at 0°C, changes in its behavior are shown concerning as-received steel, a significant increase in the percent shear fracture is observed, with a value of approximately 50%, indicating that this temperature corresponds (or it is very close) to the transition temperature of the material. According to the impact test results, the DBTT determined is very close to the value obtained according to the fracture appearance. At room temperature (22°C), a higher ductile behavior is evident, with a percent shear fracture of 85%. Above 40°C, totally ductile behavior is observed, with a percent shear fracture of 100%. The values obtained indicate a reduction in the transition temperature of the material after heat treatment in agreement with the results obtained in impact testing, a correct tendency and reliability of the observed behavior are ensured.

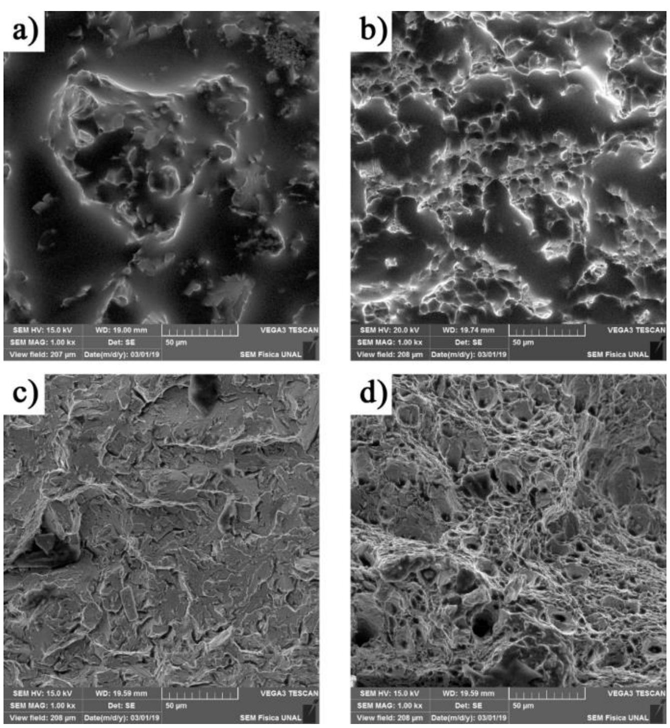

Figure 6. SEM micrographs of fracture surface for as-received (a, b) and heat-treated (c, d) steel. Brittle behavior (a, c) and ductile behavior (b, d). Source: The authors

Fig. 6 shows the fracture morphology obtained by SEM, presenting an important difference between the surfaces of as-received (Fig. 6a and 6b) and heat-treated steel (Fig. 6c and 6d). The brittle behavior (Fig. 6a and 6c) has a smooth and flat surface, with a granular appearance in both cases, although the heat-treated steel shows a higher amount of "individual" surfaces segments and smaller plastic deformation. For ductile behavior (Figure 6b and 6d), a rough surface is evident in both cases, with the presence of microvoids in the cross-section of the material produced by the plastic deformation. However, as-received steel remained with a smooth appearance in some regions, while heat-treated steel presents a higher amount of microvoids, accompanied by a refinement on the fracture surface.

The fracture surface presents a notable change after heat treatment, exhibiting an increased toughness caused by an enhancement in the plastic strain capacity. The increase in energy absorbed at low temperatures and decrease in the cleavage and/or separation surfaces of the crystallographic planes in the brittle fracture is caused principally by the refinement of the microstructure by bainitic transformation and slight plastic deformation evidenced. On the other hand, the significant change in ductile fracture morphology is also due to microstructure refinement (and other phases present in the fine microstructure obtained), giving a considerable number of stress concentrators, generating the formation of dimples by the plastic deformation, and therefore, a significant increase in the nucleation of plastic deformation.

The increase in toughness, concerning the microstructure and the heat treatment used, is due to the microstructural refinement obtained by the bainitic transformation. The fine size of the bainitic plates acts as an obstacle to the propagation of cracks, increasing its ability to absorb energy and, therefore, their toughness, a phenomenon also analyzed in-depth by Pickering [27]. A very higher microstructural refinement to nano bainite levels has demonstrate an important increase in toughness [28,29].

The high density of dislocations and the small precipitated in martensite and ferrite are other factors that could increase toughness by bainitic transformation [30]. Other studies report the formation of granular bainite from a continuous cooling treatment with the presence of austenite and martensite [21,31]. According to Qiao [31], the granular bainite formation can have two mechanisms from the cooling rate: the growth of ferrite equiaxial and the growth of plate-shaped ferrite that is evolved from carbon-rich austenite. By increase in cooling rate, the fraction of granular bainite increases, and consequently toughness increases [8].

IV. CONCLUSIONS

Bainitic transformation in low carbon steel occurs due to continuous cooling treatment and annealing. This transformation produces a microstructural refinement regarding ferrite-perlite, generating a deviation in the crack propagation path enhancing impact toughness and decreasing its brittle-ductile transition temperature.

An increase from 97 J to 159 J (64%) on impact toughness steel was obtained by the heat treatment. The brittle-ductile transition temperature had a reduction of 50ºC to -5ºC in the DBTT region, also showing a scattering of results on the transition region. In the same way, the fracture surface presents a notable change after heat treatment, the refinement of the microstructure by bainitic transformation generates a fracture surface with a major ductile area for temperatures tested.

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