EVALUATION OF THE DUCTILE-TO-BRITTLE TRANSITION TEMPERATURE IN STEEL LOW CARBON

Cássio Melo Moura¹, Jefferson José Vilela¹, Emerson Giovani Rabello², Geraldo de Paula Martins³, and José Rubens Gonçalves Carneiro²

¹ Centro de Desenvolvimento da Tecnologia Nuclear (CDTN)
Av. Prof. Mário Werneck, S/N
30123-970 Belo Horizonte, MG
jjv@cdtn.br

² Centro de Desenvolvimento da Tecnologia Nuclear (CDTN)
Av. Prof. Mário Werneck, S/N
30123-970 Belo Horizonte, MG
egr@cdtn.br

³ Centro de Desenvolvimento da Tecnologia Nuclear (CDTN)
Av. Prof. Mário Werneck, S/N
30123-970 Belo Horizonte, MG
rpm@cdtn.br

ABSTRACT

The aim of this study was evaluated the ductile-to-brittle transition temperature (DBTT) by five different methods: lateral expansion, shear fracture appearance, the average between lower and upper-shelf, load diagram and master curve using instrumented Charpy tests with total impact energy was 300 J and the impact velocity was 5.12 m/s. The Charpy specimens were 10 x 10 x 55 mm according to ASTM E-23. The load diagram showed one approach to measure when shear fractures become 50 %. Quantitative fractographic analyses of Charpy specimens reveal a certain proportion of ductile fracture even if the Charpy test is conducted at low temperatures, below the transition temperature. The ductile fracture area situated next to the notch was correlated to fracture energy for all temperatures. In the transition temperature range, fracture energy and the ductile area had a large scatter. A model for ductile-to-brittle fracture mode transition has been developed. Master curve was applied and one direction results were good.

1. INTRODUCTION

Impact tests are designed to measure the energy corresponds to the work done to fracture a specimen when suddenly applied force. Tough materials absorb a lot of energy, whilst brittle materials tend to absorb very little energy prior to fracture [1].

Paper The toughness of ferritic steels reduces when the temperature is reduced. The fracture mode changes from ductile to brittle [2]. The ductile-brittle transition temperature (DBTT) could be defined in terms of lateral expansion, percentage of shear fracture (PSF), load diagram, the average between lower and upper-shelf [3] [4] and master curve [5].
The Charpy test provides a measure of the energy required to breaking a material under impact loading. The results of these impact tests cannot be used directly to predict in-service behavior and failure characteristics, because as stated previously fracture mode depends critically, not only on the properties of the material, also other parameters. The advantages of the Charpy test are that it is quick and relatively easy to perform. It is a very useful test for assessing the quality of a product and for evaluating new products. However it does have several disadvantages, since the energy to fracture depends critically on the sample geometry, the shape and sharpness of the notch and is very dependent on the strain rate [6]. Many structures or components do not contain notches of the type used in Charpy tests or are subjected to the strain rates different that used in the Charpy test [7]. Thus, it may be misleading to directly apply the results to real industrial applications.

Charpy test specimens normally measure 55 x 10 x 10 mm and have a notch machined across one of the larger faces. The notches may be: V-shaped notch, 2 mm deep, with 45° angle and 0.25 mm radius along the base or U-notch or keyhole notch, 5 mm deep notch with 1 mm radius at the base of the notch. The notch serves as a stress concentration zone. The notch depth and tip radius have little dimensional tolerance [8].

The Charpy test consists essentially in the falling weight in the form of a pendulum that strikes a notched specimen, the weight and dimensions of the arc determine the amount of kinetic energy is generated. The maximum kinetic energy is reached at the lowest point of the swing where the specimen is supported at both ends as a simple beam. The striker mounted at the end of a pendulum reaches the specimen side without notch. After impact the specimen would be fractured or be severely strained. The pendulum continues to travel to a maximum height on the other side. The difference between initial height and post impact height is directly correlated with the absorbed energy in fracturing the specimen. The energy was recorded and the fracture mode was analyzed.

The percent ductile fracture can be estimated from the fracture appearance. Cleavage or brittle fracture could be distinguished. Brittle surface has a sparkly appearance caused by the smooth cleavage facets catching and reflecting light. In contrast, shear or ductile fracture is microscopically rough and light is scattered over all ranges of angles, hence the fracture appears dull. DBTT corresponds to the fracture surface of the broken specimen is 50 % brittle and 50 % ductile [3].

Several ferritic steels show great dispersion in transition region that creates necessity of statistics treatment [9]. A statistical experiments model called Master Curve was developed which in applied for some ferritic steels. The methodology was defined in ASTM E-1921 [5] standard for estimate the $T_0$.

The Master Curve is based on the Distribution of Weibull that defines the relation between $K_{JC}$ and the probability of fail through Equation 1 [5].

$$P_f = 1 - \exp \left[ -\left( \frac{K_{JC(average)} - K_{min}}{K_0 - K_{min}} \right)^{n} \right]$$

\(1\)
Where $P_f$ is probability of fail, $K_{JC(average)}$ is critical toughness of the material, $K_{min}$ is theoretical lower limit for the critical toughness that is considered 20MPa.m$^{1/2}$ and $K_0$ is a scale parameter of the Weibull distribution determined by Eq. 2:

$$K_0 = \left[ \sum_{i=1}^{N} \frac{(K_{JC(i)} - K_{min})^4}{N} \right]^{1/4} + K_{min} \tag{2}$$

Where, $N$ is number of tests. The $K_{JC}$ is described to Master Curve (Eq. 3).

$$K_{JC(mod)} = 30 + 70\exp\left[0.019(T - T_0)\right] \tag{3}$$

In this equation, $T_0$ is the reference temperature that correspond $K_{JC} = 100 \text{ MPa.m}^{1/2}$ [10].

The objective of this work was to compare several approaches to define Ductile/Brittle Temperature Transition in low carbon steel.

2. METHODOLOGY

The material studied in this work was the ABNT 1016 steel supplied by the GERDAU AÇOMINAS S/A. The chemical composition is showed in the Tab. 1.

**Table 1. Chemical composition of the ABNT 1016 steel.**

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Ti</th>
<th>Nb</th>
<th>Al</th>
<th>N(ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14</td>
<td>0.96</td>
<td>0.19</td>
<td>0.013</td>
<td>0.006</td>
<td>0.03</td>
<td>0.03</td>
<td>0.01</td>
<td>0.006</td>
<td>0.003</td>
<td>0.003</td>
<td>0.033</td>
</tr>
</tbody>
</table>

Charpy specimens were machined according to standard ASTM E-23 with notches in form of V in L-T and T-L directions according to the standard ASTM E-399 [11]. In L-T direction, crack plane was perpendicular to the rolling direction. In T-L direction, crack plane was parallel to the rolling direction. The samples were tested in temperatures –196 ºC, –80 to 100 ºC.

The impact tests were performed in the equipment INSTRON WOLPERT PW30, capacity 300 J and impact velocity was 5.12 m/s. The data was obtained from load cell in the striker which was connected to one acquisition system with capacity of 2.5 MHz. The data was processed in an amplifier G-100 and the program IMPACT, version 2.75 made by INSTRON.

The lateral expansion measurement methods must take into account the fact that the fracture path seldom bisects the point of maximum expansion on both sides of a specimen [12] [8].

The fracture surfaces of a broken specimen could be totally cleavage or ductile, and it also could be combinations of both. The DBTT was that one whose specimens present 50% of ductile aspect and 50% of cleavage aspect on its fracture area. For the determination of the
percentage of shear fracture, a mesh with 36 knots was placed on the photograph of the broken surface. After the delimitation of the ductile area, the number of knots contained inside of it was counted, and its ratio for the total knots number, 36, was the percent shear area.

The critical toughness \( K_{IC} \) was estimated by Eq. 4 [13], based on the values of the absorbed energy, \( E \), in the corresponding upper-shelf in transition ductile-fragile curve.

\[
K_{IC} = 0.804\sigma_{ys} \left[ \frac{E}{\sigma_{ys}} - 0.0098 \right]^{0.5}
\]  \hspace{1cm} (4)

Where \( \sigma_{ys} \) the limit of yielding was 211.13 MPa [14] and Young Modulus (E) was considered 210 GPa. ASTM E-1921 [5] establishes a value of \( K_{IC\text{,limit}} \) which is calculated by Eq. 5.

\[
K_{IC\text{,limit}} = \sqrt{\frac{Eb_{0}\sigma_{ys}}{30(1-\nu^2)}}
\]  \hspace{1cm} (5)

Where \( b_{0} \) is the thickness of specimen (10 mm) and the Poisson's coefficient (\( \nu \)) was considered 0.3. The values of \( K_{IC} \) and \( K_{IC\text{,limit}} \) were calculated for size the normalized 1T. For situations in which the specimen dimensions were different from 1T, the Eq. 6 of ASTM E-1921 was used.

\[
K_{JC(x)} = K_{min} + [K_{JC(0)} - K_{min} \left( \frac{B_{0}}{B_{x}} \right)]^{1/4}
\]  \hspace{1cm} (6)

Where \( B_{0} \) is the thickness of the specimen in fact and \( B_{x} \) is the standard thickness 1T. All \( K_{JC} \) must be below the \( K_{IC\text{,limit}} \) corrected.

\( K_{0} \) was calculated through Eq. 2, with \( K_{JC(0)} \) corresponding to \( K_{IC} \) corrected. Its determination was made considering an accumulated probability of fail of 5% aiming to adopt a conservative position.

The next step consists in the determination of reference temperature \( (T_{0}) \) by Eq. 3, using the value of \( K_{JC\text{,average}} \) calculated through Eq. 1.

3. RESULTS AND DISCUSSION

The energy-temperature curves for L-T and T-L directions were shown in Fig. 1 and 2. The L-T upper-shelf was lesser than T-L. Both curves showed good adjust with equation 7.

\[
y = A + B \tanh \left( \frac{x + C}{D} \right)
\]  \hspace{1cm} (7)
The lateral expansion-temperature curves for L-T and T-L directions were shown in Fig. 3 and 4. The L-T upper-shelf was lesser than T-L similar the energy-temperature curve. Both curves showed good adjust with equation 7.

\[
\text{Model: } y = A + B \tanh\left(\frac{x + C}{D}\right)
\]

\[
\chi^2 = 78.21781
\]

\[
R^2 = 0.98858
\]

\begin{align*}
A & \quad 95.80266 \pm 2.70049 \\
B & \quad -88.53938 \pm 3.16787 \\
C & \quad 30.84839 \pm 1.30272 \\
D & \quad -16.56475 \pm 2.81059
\end{align*}

Figure 1. Energy-temperature curve for L-T direction for 1016 ABNT steel.

\[
\text{Model: } y = A + B \tanh\left(\frac{x + C}{D}\right)
\]

\[
\chi^2 = 12.22855
\]

\[
R^2 = 0.98905
\]

\begin{align*}
A & \quad 46.83612 \pm 1.28836 \\
B & \quad 40.09957 \pm 1.56798 \\
C & \quad 10.91162 \pm 1.88842 \\
D & \quad 33.07311 \pm 3.37093
\end{align*}

Figure 2. Energy-temperature curve for T-L direction for 1016 ABNT steel.
The PSF-temperature curves for L-T and T-L directions were shown in Fig. 5 and 6. The equation 7 had good adjustment with curves. The DBTT was obtained to PSF was 50%. By this method, the DBTT's values were 24 °C higher than the ones obtained with the energy-temperature curves and lateral expansion curves.

Figure 3. Lateral expansion-temperature curve for L-T direction for 1016 ABNT steel.

Figure 4. Lateral expansion-temperature curve for T-L direction for 1016 ABNT steel.
Fig. 7 shows one example of instrumented impact Charpy test in the transition region. The unstable fractured could be observed between Pu (beginning of growth unstable crack) and Pa (beginning of lateral expansion). In this stage, the surface fracture is plane and the plastic strain is little [15]. Little energy is necessary to propagate the crack. The characteristic loads (Pa, Pgy, Pm and Pu) were obtained by instrumented impact Charpy test as show on Fig. 7. Figures 8 and 9, load-diagrams for L-T and T-L directions were shown. The adjustment of equation 8 with PSF (surface fracture appearance) was better when the constants k were –0.76 to L-T direction and –1.34 to direction T-L. Böhme [4] found constant k in range from 0 to 1.

\[
SFA = \left[1 - \frac{Pu - Pa}{Pm + k(Pm - Pgy)}\right] \times 100
\]

(8)

The DBTTs values obtained from the different methods were shown in Tab. 2.

Only for comparison, the \(K_{JC}\) at room temperature is showed in Tab. 3 and Tab. 4 for directions L-T and T-L, respectively. The results showed difference between two directions. For orientation L-T, the values of \(K_{JC(x)}\) were lower than \(K_{JC(limit)}\) and the reference temperature \((T_0)\) was 55.2°C and critical toughness \((K_{1c})\) was 69.4 MPam\(^{1/2}\) at room
temperature. For orientation T-L, the limits of $K_{SC}$ were exceeded, in way that the values proceeding from DBTT curve could not have been used.

![Graph showing PSF percentage vs temperature]

Figure 6. Percentage of shear fracture (PSF) obtained from analysis surface fracture for T-L direction for ABNT 1016 steel.

![Graph showing load-time and energy-time curves]

Figure 7. Load-time Curve and energy-time were obtained by instrumented impact Charpy test in transition region for ABTN 1016 steel. $P_{gy}$ corresponds to the transition elastic-plastic, $P_m$ is the maximum load, $P_u$ is the beginning of unstable crack and $P_a$ is the beginning lateral expansion.
Figure 8. Load diagram in L-T direction for ABNT 1016 steel.

Figure 9. Load diagram in T-L direction for ABNT 1016 steel.
Table 2. Values of DBTT calculated by different methods.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Average between upper and lower-shelf</th>
<th>Lateral expansion</th>
<th>PSF, 50 %</th>
<th>Load diagram with PSF 50 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-T</td>
<td>0 °C</td>
<td>4 °C</td>
<td>6 °C</td>
<td>6 °C</td>
</tr>
<tr>
<td>T-L</td>
<td>-33 °C</td>
<td>-30 °C</td>
<td>-6 °C</td>
<td>-6 °C</td>
</tr>
</tbody>
</table>

Table 3 - Resulted of $K_{JC}$ for direction L-T.

<table>
<thead>
<tr>
<th>$K_{JC(limit)}$</th>
<th>127,4</th>
<th>$K_{JC(x)}$</th>
<th>106,4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{JC(limit)}$ - corrected</td>
<td>105,1</td>
<td>$K_{JC(x)}$ - corrected</td>
<td>88,5</td>
</tr>
</tbody>
</table>

$K_{JC(limit)} > K_{JC(x)}$, OK!

<table>
<thead>
<tr>
<th>$K_0$</th>
<th>88,4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{JC(average)}$</td>
<td>82,5</td>
</tr>
<tr>
<td>$T_0$</td>
<td>55,2 °C</td>
</tr>
<tr>
<td>$K_{JC}$ – room temperature</td>
<td>69,4</td>
</tr>
</tbody>
</table>

Table 4 - Resulted of $K_{JC}$ for direction T-L.

<table>
<thead>
<tr>
<th>$K_{JC(limit)}$</th>
<th>127,4</th>
<th>$K_{JC(x)}$</th>
<th>156,4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{JC(limit)}$ - corrected</td>
<td>105,1</td>
<td>$K_{JC(x)}$ - corrected</td>
<td>128,3</td>
</tr>
</tbody>
</table>

$K_{JC(limit)} > K_{JC(x)}$, fail, limit value was used

<table>
<thead>
<tr>
<th>$K_0$</th>
<th>105,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{JC(average)}$</td>
<td>97,7</td>
</tr>
<tr>
<td>$T_0$</td>
<td>11,8°C</td>
</tr>
<tr>
<td>$K_{JC}$ – room temperature</td>
<td>119,9</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

The directions showed strong influence in the DBTT values - the difference between L-T and T-L was about 30 °C.

The adopted values in the constant k of model for ductile-to-brittle fracture mode transition (Eq. 8) were −0.76 to L-T direction and −1.34 to direction T-L.
In all studied methods, the Temperature-Energy Curve showed good adjustment with the tangent hyperbolic tangent equation.

The analyses carried out in this work showed the difficulties to determine the ductile/brittle transition temperature with using several methods showed different results.

The PSF showed that the lower-shelf is 5% ductile material and upper-shelf is 95% is brittle material. The temperature associated with 50% of ductile material does not correspond to the average between lower and upper-shelf.

The evaluation of PSF showed the difficulties to obtain the characteristic loads from Charpy impact test.

The $K_{IC}$ could be calculated only in direction L-T.

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REFERENCES


