EVALUATION OF THE DUCTILE-TO-BRITTLE TRANSITION TEMPERATURE IN THE ABNT 1016 STEEL USING INSTRUMENTED CHARPY IMPACT TESTING

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Abstract. *The aim of this study was to examine the relationship between fracture energy and percentage of shear fracture (PSF) in the ABNT 1016 steel in L-T and T-L directions. L-T was crack plane perpendicular to the rolling direction and T-L was crack plane parallel to the rolling direction. Instrumented Charpy tests were performed in the transition region, as well as at lower and upper shelf. The total impact energy was 300 J and the impact velocity was 5.12 m/s. The dimensions of Charpy specimens were 10 x 10 x 55 mm. They were made according to standard ASTM E-23 (2005). The ductile-to-brittle transition temperature (DBTT) was evaluated by four different methods: lateral expansion, percentage of shear fracture (PSF), load diagram and the average between lower and upper shelf. Load diagram and quantitative fractographic of Charpy specimens were used to estimate when the percentage of shear fracture was 50 %. The model for ductile-to-brittle fracture mode transition was developed and compared with PSF. The values of constant k were –0,76 to L-T direction and –1,34 to direction T-L. The directions showed influence in DBTT and difference between L-T and T-L was about 30 °C.*

Keywords*: Charpy testing; Ductile-to-brittle transition temperature (DBTT); Impact energy; low carbon steel*

1. INTRODUCTION

The toughness of ferritic steels reduces as the temperature is reduced. The fracture mode changes from ductile to brittle (Lei *et al*, 1993). The ductile-brittle transition temperature (DBTT) could be defined in terms of lateral expansion, percentage of shear fracture (PSF), load diagram and the average between lower and upper shelf (Walle 2003; Böhme 1996).

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 (Kim *et al.*, 2002).

The Charpy test provides a measure of the energy required 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, but another parameters. But 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 (Lei *et al*, 1993 A). 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 (Logsdon and Begley, 1997). Thus, it may be misleading to directly apply the results to real industrial applications.

Charpy test keeps as a well-recognized method of specifying steel quality. It allows comparison between different types of steel made from a variety of manufacturing processes. After the mid 1950s, welding techniques were improved and Charpy testing became an essential part of steel specification. (Logsdon, 1982).

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 are little dimensional tolerance (ASTM E-23, 2005).

The Charpy test consists essentially in the falling weight is in the form of a pendulum, the weight and dimensions of the arc determine the amount of kinetic energy generated as the pendulum swings that strike a notched specimen. 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 impacts the specimen behind a machined 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 corresponds the absorbed energy in fracturing the specimen. The energy was recorded and the fracture mode was analyzed.

The percent ductile fracture is termed shear fracture and can be estimated from the fracture appearance. It is not practical to examine Charpy specimens to estimate the amount of ductile fracture on each surface but cleavage or brittle fracture could be distinguished. It 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 the fracture surface of the broken specimen is 50 percent brittle and 50 percent ductile (Walle 2003).

The objective of this work was to examine the relationship between fracture energy and percentage of shear fracture in the ABNT 1016 steel in L-T and T-L directions.

2. Methodology

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

Table 1 – Chemical composition of ABNT 1016 steel.

C	Mn	Si	P	S	Cr	Ni	Mo	Ti	Nb	Al	N(ppm)
0,14	0,96	0,19	0,013	0,006	0,03	0,03	0,01	0,006	0,003	0,033	53

19 Charpy specimens were machined according to standard ASTM E-23. The notches in form of V were making in the Blacks Equipment broach in L-T and T-L directions according to the standard ASTM E-399 (Fig. 1). L-T was crack plane perpendicular to the rolling direction and T-L was crack plane parallel to the rolling direction. The samples were tested in temperatures –196 ºC, –80 to 100 ºC.

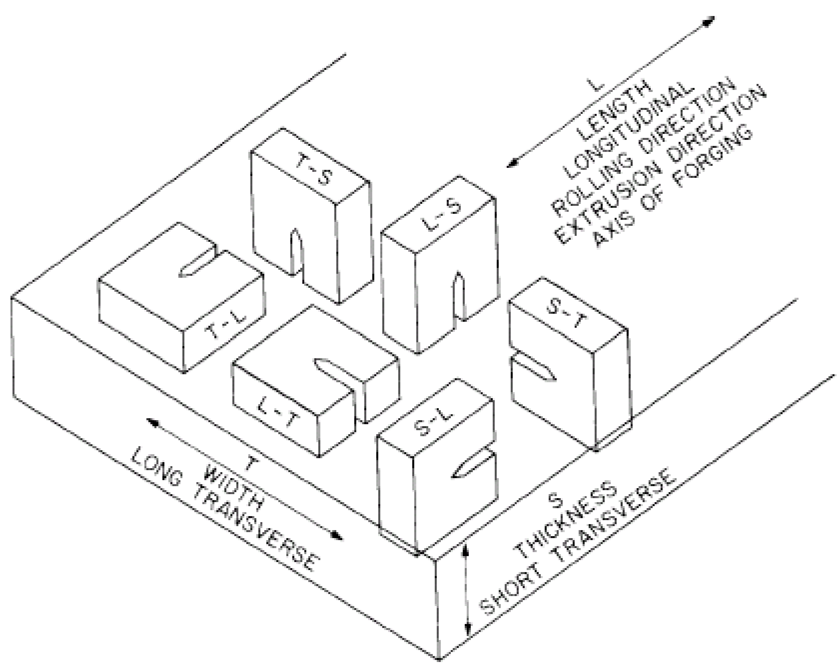

Figure 1 – Crack plane orientation code for rectangular sections. (ASTM-E399, 1997)

The impact tests were made 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 was connected one acquisition system with capacity of 2.5 MHz. The data was processed in amplifier G-100 and the program IMPACT, version 2.75 made by INSTRON then electrical signals were converted in force. The time was measured trough clock of acquisition system. The velocity striker (v), deflection specimen (s) and absorbed energy were calculated through classical mechanic.

The striker velocity (v) was calculated through change in quantity movement and integration the curve force-time.

$$\Delta Q = \int F(t).dt \tag{1}$$

$$M.v_0 - (M + m).v = \int F(t).dt \tag{2}$$

Consider M >> m, then:

$$M.(v_0 - v) = \int F(t).dt \tag{3}$$

$$v(t) = v_0 - \frac{1}{M}\int F(t).dt \tag{4}$$

where v_0 was striker velocity before impact and M was pendulum mass.

The specimen deflection was determined through integration curve force-time.

$$s(t) = \int v(t).dt \tag{5}$$

The absorbed energy was calculated though integration curves force-deflection.

$$w(s) = \int F(s).ds \tag{6}$$

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. The two halves of the specimen and its relative expansion were shown in Fig. 2. Using a micrometer, one half of the fractured specimen was taken and the reads of the instrument were recorded. A similar measurement on the other half was done. The lower value for the two halves must be disregard, and only the biggest relative expansion must be considered. Then, the lateral expansion would be the addition of these values. (ASTM-E23, 2005)

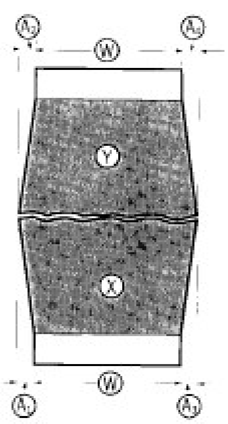

Figure 2 – Halves of broken Charpy V-notch impact specimen. (ASTM-E23, 2005)

The fracture surfaces of a broken specimen could be totally cleavage or ductile, and it also could be other combinations of both. The DBTT was that one whose speciments present 50% of ductile aspect and 50% cleavage aspect on its fracture area. The brittle regions of the fracture surface were generally bright and faceted, whilst the ductile areas dull, strained and sheared (Fig. 3).

Photographs of the specimen's fracture surfaces was taken in order to extend the resolution and, thus, to become easier the identification of the shear and cleavage areas in each one of them.

For the determination of the percentage of shear fracture, a mesh with 36 knots was placed on the photograph of the broken surface, like shown in the Fig. 4. After the delimitation of the ductile area, the number of knots contained inside of it was taken, and its reason for the total knots number, 36, was the percent shear area.

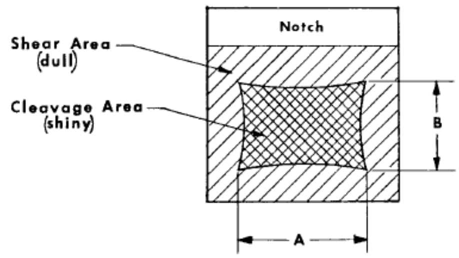

Figure 3 – Fracture surface of a Charpy V-notch impact specimen. (ASTM-E23, 2005)

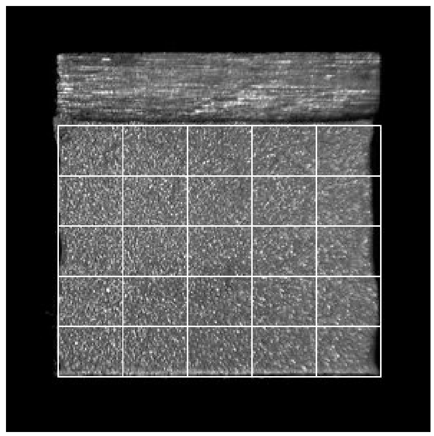

Figure 4 – Mesh on the fracture area. (Cochrane, 2007)

3. Results and discussion

The curves energy-temperature for L-T and T-L directions were showed in Fig. 5 and 6. The L-T upper-shelf was lesser than T-L. Both curves showed good adjust with equation 7.

$$y = A + B\tanh\left(\frac{x + C}{D}\right) \tag{7}$$

The curves lateral expansion-temperature for L-T and T-L directions were showed in Fig. 7 and 8. The L-T upper-shelf was lesser than T-L similar the curve energy-temperature. Both curves showed good adjust with equation 7.

The curves PSF-temperature for L-T and T-L directions were showed in Fig. 9 and 10. The equation 7 had good adjustment with curves. The DBTT was obtained to PSF was 50 %. In this method, DBTTs were 24 °C higher then curves energy-temperature and lateral expansion.

On Fig. 11 is showed one instrumented impact Charpy test in the transition region. The unstable fractured could be observed between P_u (beginning of growth unstable crack) and P_a (beginning of lateral expansion). In this stage, surface fracture was plane and plastic strain was little (MIYAZAKI; IKEDA; MIYAGI, 1996). Little energy was spent to propagate the crack.

The characteristic loads (P_a, P_{gy}, P_m and P_u) were obtained by instrumented impact Charpy test as showed on Fig. 11. Figures 12 and 13, load-diagrams for L-T and T-L directions were showed. The equation 8 was agreed with PSF (surface fracture appearance). The constants k were –0,76 to L-T direction and –1,34 to direction T-L. The Böhme (1996) found constant k between 0 to 1.

$$SFA = \left[1 - \frac{Pu - Pa}{Pm + k(Pm - Pgy)}\right] \times 100 \tag{8}$$

The DBTTs obtained for different methods were showed in Tab. 2.

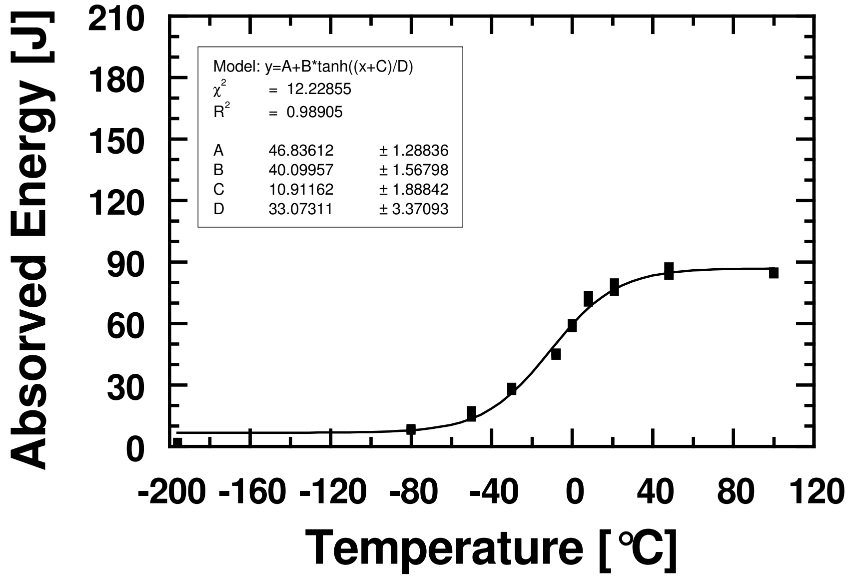

Figure 5 – Curve energy-temperature of L-T direction for 1016 ABNT steel.

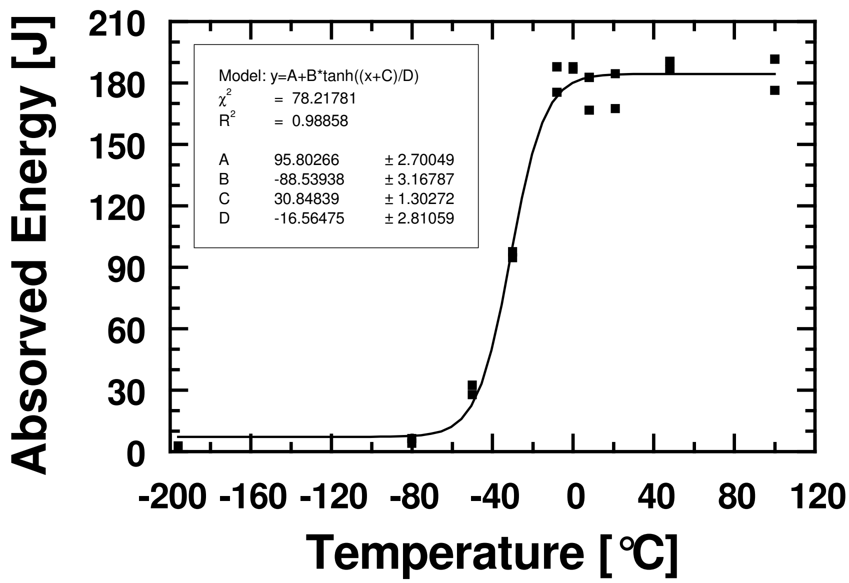

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Figure 6 – Curve energy-temperature of T-L direction for 1016 ABNT steel.

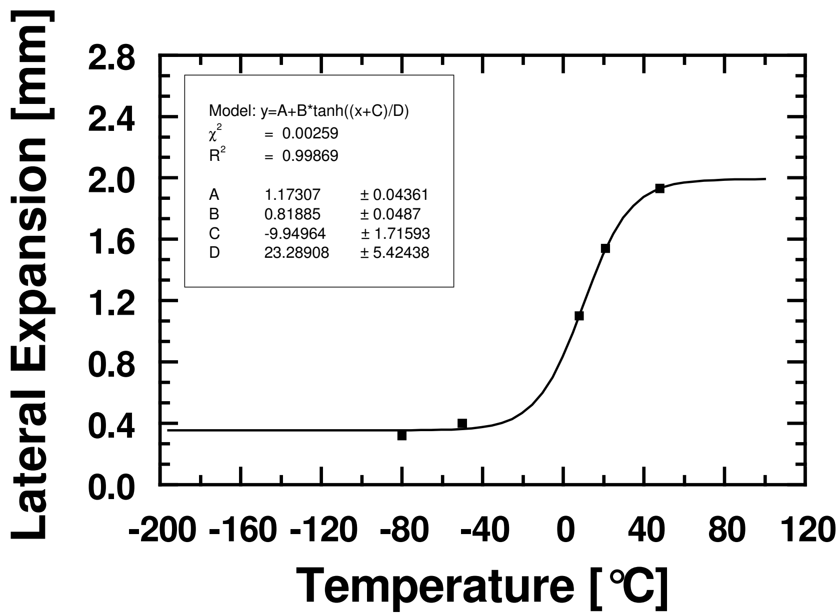

Figure 7 – Curve lateral expansion-temperature of L-T direction for 1016 ABNT steel.

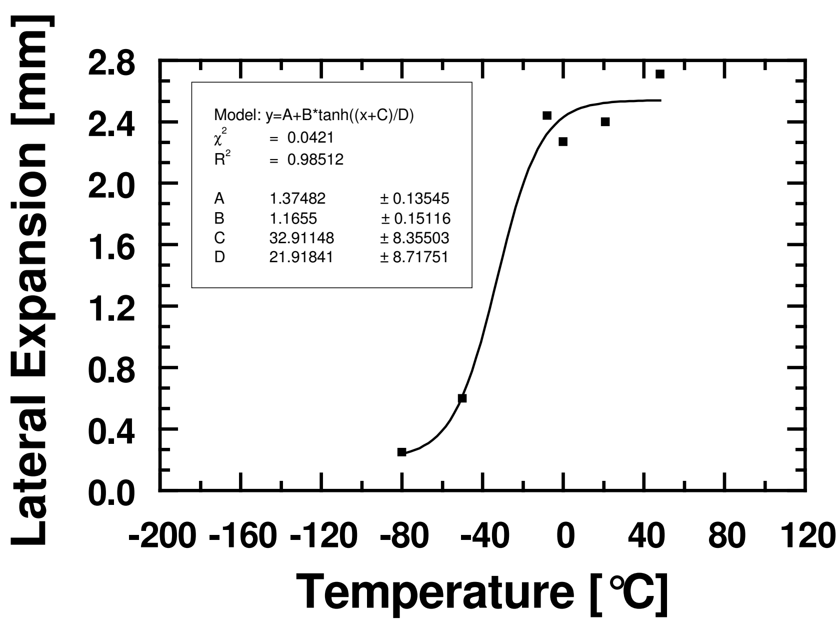

Figure 8 – Curve lateral expansion-temperature of T-L direction for 1016 ABNT steel.

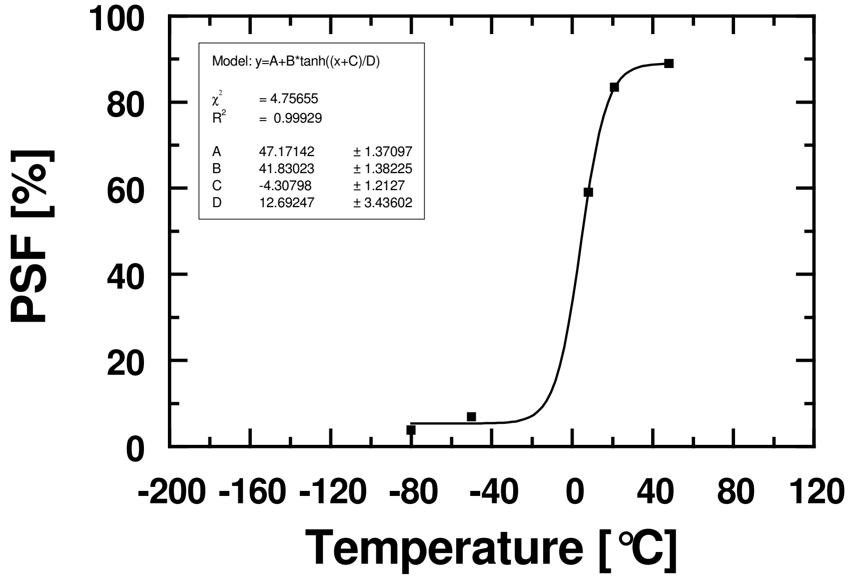

Figure 9 – Percentage of shear fracture (PSF) obtained from analysis surface fracture to L-T direction for ABNT 1016 steel.

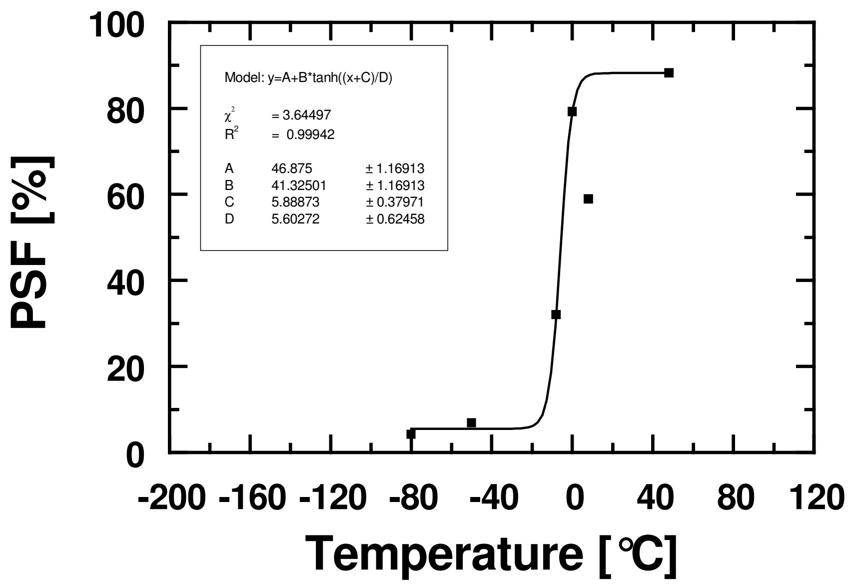

Figure 10 – Percentage of shear fracture (PSF) obtained from analysis surface fracture to T-L direction for ABNT 1016 steel.

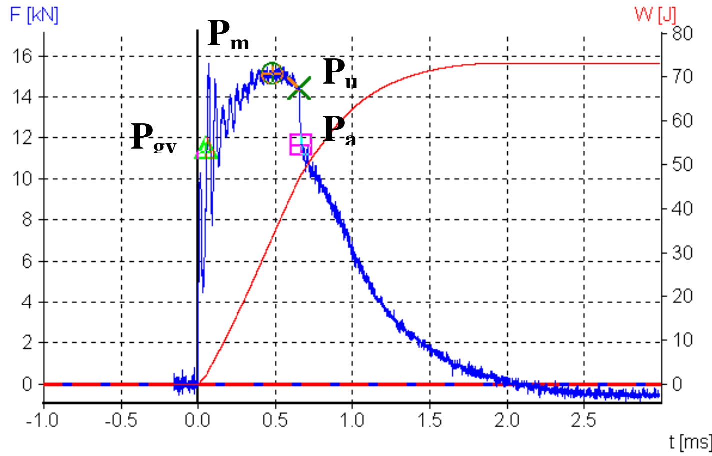

Figure 11 - Curves load-time and energy-time were obtained by instrumented impact Charpy test in transition region for ABTN 1016 steel. P_{gy} was corresponded transition elastic-plastic, P_m was maximum load, P_u was beginning unstable crack and P_a was beginning lateral expansion.

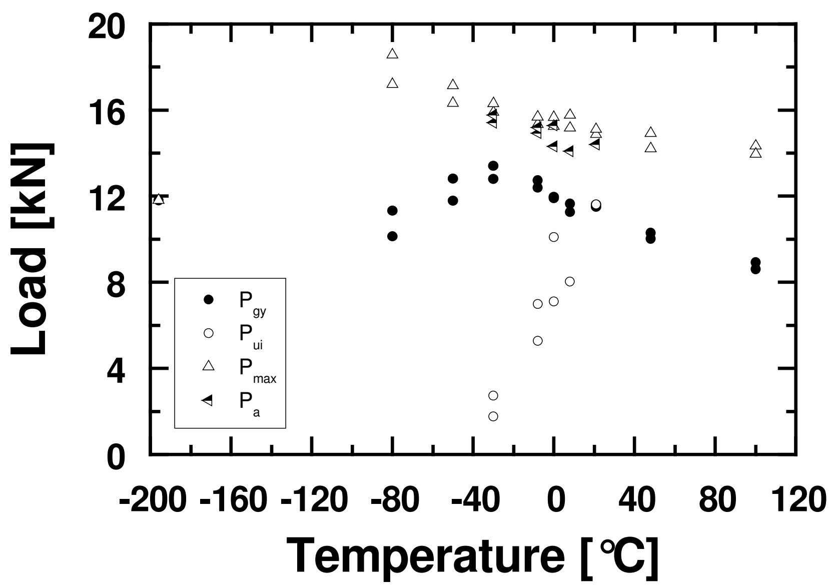

Figure 12 – Load diagram in L-T direction for ABNT 1016 steel.

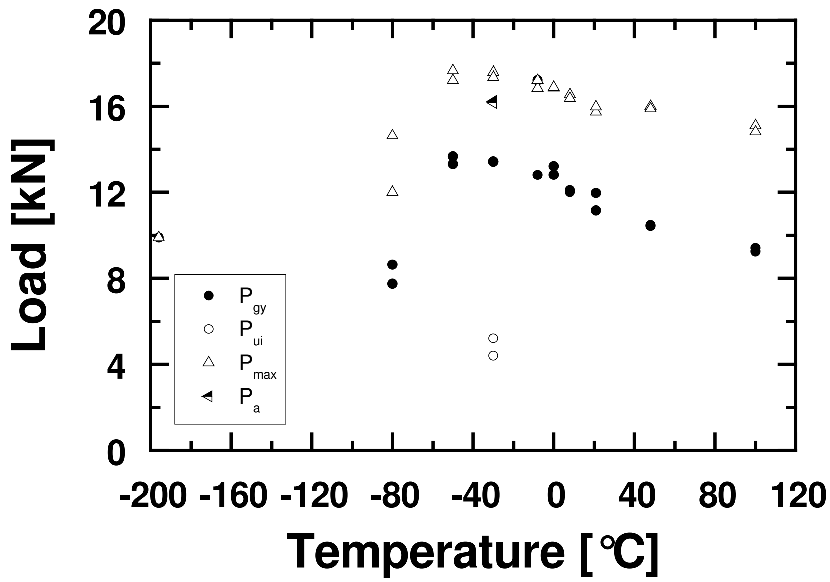

Figure 13 – Load diagram in T-L direction for ABNT 1016 steel.

Table 2 - Values of DBTT calculated by different methods.

Direction	Average between upper and lower shelf	Lateral expansion	PSF, 50 %	Load diagram with PSF 50 %
L-T	0 °C	4 °C	6 °C	6 °C
T-L	-33 °C	-30 °C	-6 °C	-6 °C

4. Conclusion

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

The values of constant k of model for ductile-to-brittle fracture mode transition (equation 8) were –0.76 to L-T direction and –1.34 to direction T-L.

In all studied methods, the curve Temperature-Energy showed good adjust with tangent hyperbolic tangent equation.

5. Acknowledgements

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