Evaluation of Dynamic Fracture Mechanics in the AISI 316 Stainless Steel Using Instrumented Charpy Impact Testing

Bruno Jardim França Rodrigues[1], Juliano Daniel de Carvalho[2], Jefferson José Vilela[3] and Geraldo de Paula Martins[3]

[1]Engineer of Novo Nordisk, Montes Claros, MG, Minas Gerais, Brazil
[2]Engineer of Empresa Brasileira de Aeronáutica S.A. (EMBRAER), São José dos Campos, São Paulo, Brazil
[3]Researcher of Nuclear Technology Development Center/Nuclear Energy National Commission, Belo Horizonte, Minas Gerais, Brazil

ABSTRACT

The dynamic fracture mechanics behavior of the AISI 316 stainless steel was studied by using instrumented Charpy impact testing. The dynamic fracture toughness (J_{1d}) could be evaluated by four different methods: Compliance Changing Rate, Stretching Zone, Energy Revised and Maximum Load Energy. The tests were made in temperatures −196 ºC, room and 200 ºC. At each temperature two specimens were tested. The total impact energy was 300 J and the impact velocity was 5.12 m/s. The Charpy specimens 10 x 10 x 50 mm were pre-cracked until 5 mm according to ASTM E-23. Stretching zone size was measured and analyzed by observing the fracture surfaces. They were obtained in a scanning electron microscope. Some times the blunting angle (θ) is assumed to 45°, but in this work it was the measured directly of stretching zone width. The range of θ?changed from 22 to 27º. The dynamic fracture toughness calculated among the three different methods showed a large difference. The compliance method showed less conservative. The values obtained by the revised energy were between the compliance and stretching zone methods. The AISI 316 stainless steel showed an extremely ductile behavior between −196 °C and 200 ºC. All methods did not agree ASTM E1820 standard. In this work, plane strain was not occurred in the tip crack in the AISI 316.

Keywords: Charpy testing; stretching zone; compliance changing rate; dynamic fracture; AISI 316 stainless steel

INTRODUCTION

In many nuclear power plants, there are many machines with more than thirty years old that need the structural integrity evaluation and life extension programs. Mechanisms of fracture are usually used for these evaluations.

Up to the present moment, there is not a complete approach to characterize and measure the dynamic fracture toughness of several materials. The theories and experimental techniques are still being developed. Nowadays, the parameters of dynamic fracture mechanics are normally obtained through instrumented Charpy test through pre-crack samples.

The objective of this work was to obtain the parameters of dynamic fracture in the AISI 316 stainless steel by using instrumented Charpy impact test.

Compliance method

During the dynamic loading, the compliance increases abruptly when the crack starts propagating and strength of material reduces.

The intensity of changing compliance is calculated through:

$$\frac{\Delta C}{C} = \frac{C - C_{el}}{C_{el}} \tag{1}$$

Where C is linear compliance that is obtained through:

$$C = \frac{\Delta f}{\Delta P} \tag{2}$$

Where ?f is the variation of displacement and ?P is the variation of load along the curve. C_{el} is a division between displacement and yielding load:

$$C_{el} = \frac{f_y}{P_y} \tag{3}$$

Where P_y is the yielding load and f_y is the displacement correspondent to this load.

Outset the propagation of crack is obtained through the curve ΔC/C x displacement. It starts when a great change occurs in the curve. The energy (E_i) is calculated until this point and toughness (J_{Id}) can be evaluated by Equation 4.

$$J_{Id} = \frac{2.E_i}{B.(W - a_0)} \tag{4}$$

Where B is the thickness of the specimen, W is the width and a_0 is the initial length of the crack.

Measurement of stretching zone

In the elastic-plastic condition, the stretching zone (Fig. 1) is created due to stress concentration at the tip of the crack. Besides that, this concentration provokes slipping of crystalline planes that drive to plastic strain. The toughness (J_{Id}) can be calculated using the critical stretching zone width (SZW_c) (Eq. 5) [1]. That is measured on the fracture surface of the specimen.

$$J_{Id} = \frac{d_{pl} \times E}{222,5} \tag{5}$$

Where E is Young Modulus and δ_{pl} is the displacement up to the fast propagation of crack.

$$d_{pl} = 2 \times \tan q \times SZW \tag{6}$$

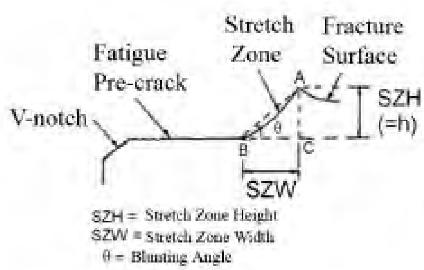

Figure 1. Profile of the stretching zone [1].

Revised energy method

The propagation of crack start before the maximum load [2]. However, the principle of this method is revised the maximum load energy (E_m) that is obtained from curve load-displacement through the set of Equations 7 to 10. The revised energy (E_{mr}) calculated represents the critical energy from start the propagation of crack [3] [4].

$$J_{Id} = \frac{2.(E_{mr})}{B.(W - a)} \tag{7}$$

$$(E_{mr}) = E_m - \left(\frac{P_m^2}{2}\right)\left[\left(\frac{v_0.t_y}{P_{gy}}\right) - \left(\frac{v_0^2.t_y^2}{8.E_0}\right) - \left(\frac{C}{B.E}\right)\right] \tag{8}$$

$$C = 72.\left[g\left(\frac{a}{W}\right)\right] + 2 \quad (9)$$

$$g\left(\frac{a}{W}\right) = 1{,}86.\left(\frac{a}{W}\right)^2 - 3{,}95.\left(\frac{a}{W}\right)^3 + 16{,}38.\left(\frac{a}{W}\right)^4 - 37{,}23.\left(\frac{a}{W}\right)^5 + 77{,}55.\left(\frac{a}{W}\right)^6 - \\ - 126{,}87.\left(\frac{a}{W}\right)^7 + 172{,}53.\left(\frac{a}{W}\right)^8 - 143{,}90.\left(\frac{a}{W}\right)^9 \quad (10)$$

Where, v_0 (5.12 m/s) is the impact velocity of tup, t_{gy} is the time that corespondent to yielding load (P_{gy}), a_o is the initial length of crack, E_o (300 J) is the total energy of impact, C is the compliance do specimen and g(a/W) is function that change with geometry of sample.

Maximum energy method

The dynamic toughness fracture (J_{Id}) is calculated according to maximum load energy:

$$J_{Id} = \frac{2.E_m}{B.(W - a_0)} \quad (11)$$

METHODOLOGY

The material studied in this work was the AISI 316 austenitic stainless steel supplied by the Special Steels Itabira (ACESITA). The chemical composition is showed in the Tab. 1.

Table 1. Chemical composition of austenitic stainless steel 316.

C	**Mn**	**Si**	**P**	**S**	**Cr**	**Ni**	**Mo**
0.03	1.49	0.55	0.031	0.003	17.47	11.1	2.04
Al	**Cu**	**Co**	**V**	**Nb**	**Ti**	**N (ppm)**	
0.011	0.19	0.15	0.03	0.006	0.0021	417	

Six Charpy specimens were machined from bars of size 20 x 20 x 150 mm according to standard ASTM E-23 [5]. The length was parallel to direction rolling. The notches in form of V were make in the Blacks Equipment broach in the direction L-T according to the standard ASTM E-399 [6]. The samples were tested in temperatures –196 ºC, room and 200 ºC, two testes were made each temperature. All specimens were pre-cracked up to 5 mm in the servo-hydraulic machine INSTRON model 8802 with capacity 250 kN.

The impact tests were made in the equipment INSTRON WOLPERT PW30, capacity 300 J and the impact velocity was 5.12 m/s. Besides that, the data was obtained through an amplifier G-100 of 2500 kHz and the program IMPACT, version 2.75 made by INSTRON. The data of impact test usually needs a smoothing approach due to oscillations loads received in strain gages. The curve load-time was smoothed through fast Fourier transform (FFT) of Origin 6.1. The maximum load energy was obtained after the using smoothing approach.

The stretching zone was measured in three different positions in each specimen, for angles a: 0°, 20°, 40° and 60°, add up 12 measurements for each specimen. The angle ? was determined from SZH (stretching zone height). A trigonometry relationship was used to obtain SZW [1]. The fracture surface was characterized through the scanning electronic microscope Jeol, model JSM 5310.

The curve stress-strain was obtained through tensile test that was executed in the machine INSTRON TTDML. The module of elasticity was measured and used in the calculation of J_{Id}.

RESULTS AND DISCUSSION

Impact test

Six curves of Charpy impact test in the temperatures –196 °C, room and 200 ºC were obtained. Two tests were made for each temperature (Fig. 2).

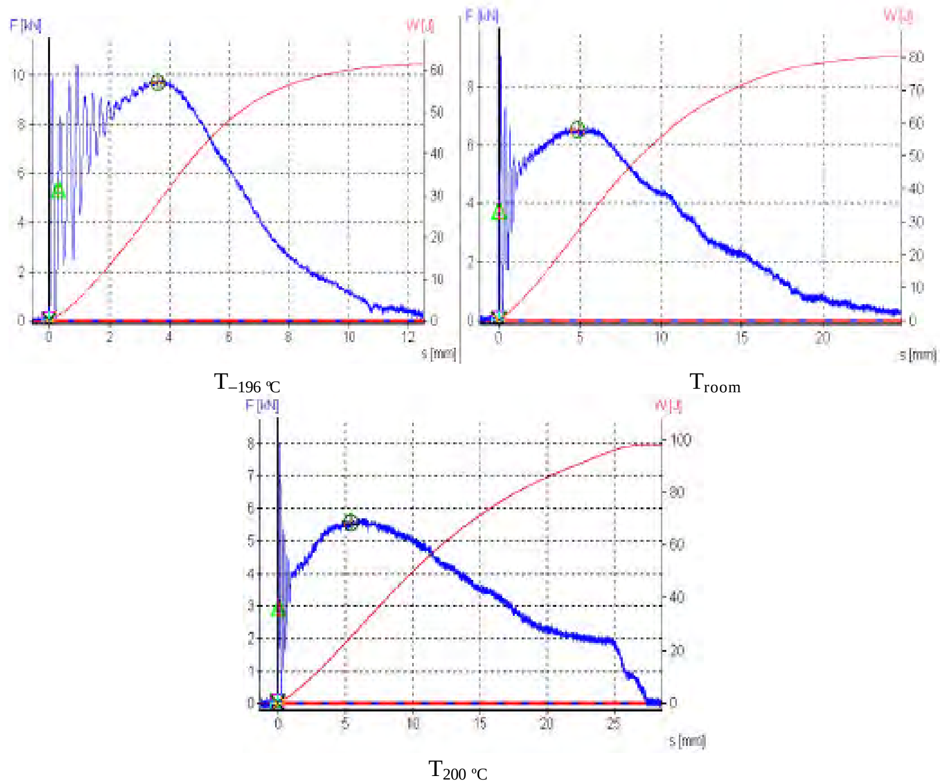

Figure 2. Curves of Charpy impact test at three different temperatures.

As expected, the total absorbed energy increases with the temperature. But, the variation of this energy was small. The largest value of maximum load occurs at –196 °C and the smallest at 200 ºC. The material was ductile in the range of temperature –196 °C to 200 ºC. The austenitic stainless steel 316 did not show ductile-fragile.

Estimate of J_{Id} by the Compliance Method

The electronic acquisition showed noises that difficult application of the compliance method. The method took in consideration the instantaneous variation of the load, so it was necessary that the curves were smoothed. The technique FFT (Fast Fourier Transform) was used to smooth the curves (Fig. 3). The point where the abrupt variation of the compliance occurred was considerate the outset propagation of the crack (Fig. 4). The energy corresponding to the propagation beginning was measured (Fig. 5) and, the resistance values for the dynamic fracture for different temperature conditions were calculated (Tab. 2).

Table 2. Values of J_{Id} calculated by the compliance method.

	$T_{-196°C}$	T_{room}	$T_{200°C}$
J_{Id} (kJ/m^2)	788.29	547.43	797.43
	637.43	624.57	739.71
Average	712.86	586.00	768.57

The J_{Id} obtained through this method was more conservative. The point where the variation of the compliance was abrupt did not correspond to the maximum load of the test. This indicated that the propagation of crack happened with load values below the maximum load.

The value of J_{Id} in the room temperature was smaller than –196 ºC. But, the materials in the low temperature became little more fragile. A statistical evaluation with more amounts of tests could be made.

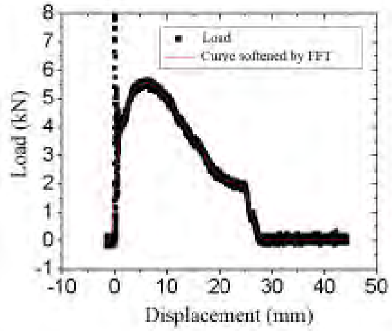

Figure 3. Curve smoothed by FFT, T = 200 ºC.

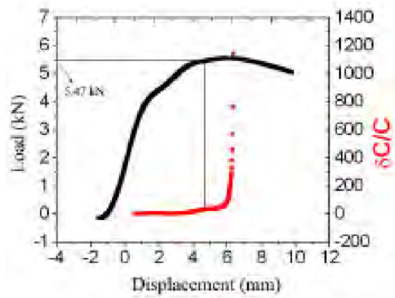

Figure 4. Variation of Compliance, T=200 ºC.

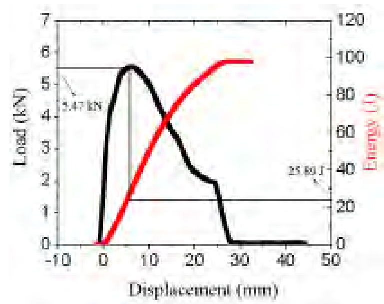

Figure 5. Energy associated to the beginning of the abrupt variation. T=200 ºC.

Estimate of J_{Id} for the Stretching Zone Method

The technique proposed by Sreenivasan [1] that was used to obtain J_{Id} (Fig. 6). The values of d were measured in the angles: 0º, 20°, 40° and 60° in three specimens. The results obtained from specimen tested at –196 °C are showed in Fig. 7.

It was observed in all tests that the projection d showed larger values in high temperatures. The measures were made in three positions of the stretching zone along the thickness of the specimen. The average values of the SZW and blunting angle (θ) are showed in the Tab. 3.

The increase of the temperature involved an increase in toughness that generated a stretching zone with larger width. The stretching zone was not completely uniform. Havel [7] obtained the values of SZW for the stainless steel 316 aged that varied from 0.11 to 0.56 mm. These measures were done directly on the surface of fracture.

Plane tensions could be difficult to measure the stretching zone due to changing the intensity of the plastic strain. So, the height of the stretching zone would not represent the real point of crack opening [8]. The medium values of SZW and θ became possible to determine the value of the dynamic fracture toughness using the stretching zone method (Tab. 4).

The stretching zone method was less conservative than the compliance method. The difference between them reached 157 %. The dynamic fracture toughness obtained by the stretching zone method was minor at the room temperature. The same occurred with the compliance method. It is necessary a better statistical approach using a higher number of specimens in the tests.

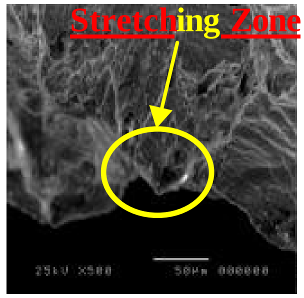

Figure 6. Aspect of the Stretching Zone obtained by Scanning Electronic Microscope.

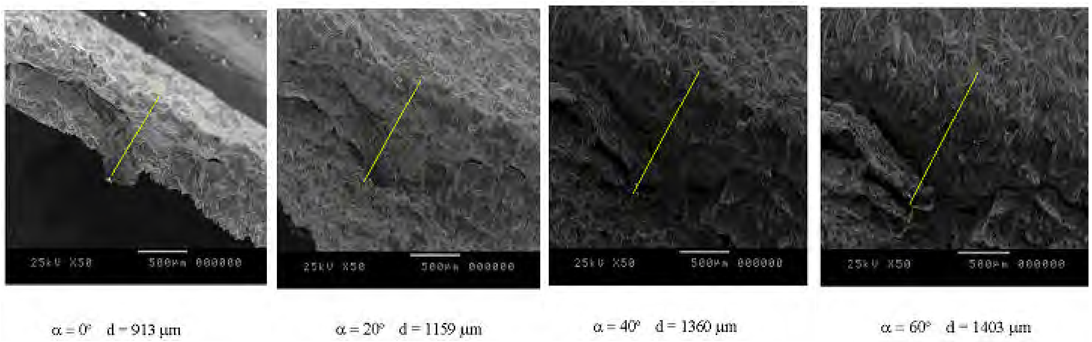

Figure 7. Measures of d for several inclination angles of the specimen (T = - 196 °C).

Table 3. Average values of SZW for three temperatures.

	$T_{-196\,°C}$	T_{room}	$T_{200\,°C}$
SZW $_{average}$ **(m)**	0.001699 ± 6.8x10^{-4}	0.001877 ± 1.5x10^{-4}	0.002777 ± 1.5x10^{-4}
$\theta_{average}$ **(°)**	27.54 ± 10.78	22.22 ± 3.16	23.45 ± 5.19

Table 4. J_{Id} values calculated by the stretching zone method using the equation proposed by Sreenivasan [1].

	$T_{-196°}$	T_{room}	$T_{200°}$
J_{Id} **(kJ/m^2)**	1401.03	1213.29	1905.78

Values of J_{Id} calculated in the literature for AISI 316 aged and tested at room temperature varied from 69 to 685 kJ/m^2 [1]. The value AISI 321 obtained by impact test was 421 kJ/m^2 [9]. And, the values J_{Id} for the stainless steel 304 were 400 to 440 kJ/m^2 [10]. Sreenivasan [1] told that probably the influence of the tension level at room temperature was small. The J-R Curves obtained for the stainless steel 316 [11] indicated toughness values above 600 kJ/m^2. In the author's opinion, the stainless steels 304 are more sensitive to the stress variation than 316.

Estimate of J_{Id} for the revised energy method

The results of through revised energy method were showed in the Tab. 5. In the values of maximum load energy (E_m) were obtained through smooth curves. Maximum load (F_m), yielding load (F_{gy}) and time up to maximum load (t_{gy}) were used to calculate J_{Id} through revised energy and maximum load energy.

According to Xinping and Yoawu [3], the values of J_{Id} for maximum load energy were fewer conservatives or the energy to propagation was larger in this method. But, in this work, J_{Id} obtained through stretching zone was less been conservative yet (Fig. 7).

The values of J_{Id} from revised energy showed the best results according to Xinping and Yoawu [3]. Because, in their work, the J_{Id} was similar to values obtained to curve J-R method that use several specimens. And, this method was considered the standard value. Their work the difference between two methods was 1.2 %, and, between revised energy and compliance was 7 %, in this work, it was up to 30 %.

In this work, the values of J_{Id} in −196 °C were more value than in room temperature for all methods (Tab. 6).

The figure 9 shows that all methods and material did not agree ASTM E1820 standard [12]. In this work, plane strain was not occurred in the tip crack in the austenitic materials.

Table 5. Values of J_{Id} calculated by the maximum load energy and revised energy methods.

Temperature [ºC]	E_m [J]	E_{mr} [J]	F_m [kN]	F_{gy} [kN]	t_{gy} [ms]	J_{1d}, E_{mr} [kJ/m^2]	J_{1d}, Em [kJ/m^2]
-196	29.508	27.035	9.917	4.404	0.055	1081.42	1180.33
25	24.645	22.936	6.557	3.306	0.059	917.44	985.80
200	28.892	27.192	6.265	3.113	0.060	1087.68	1155.68

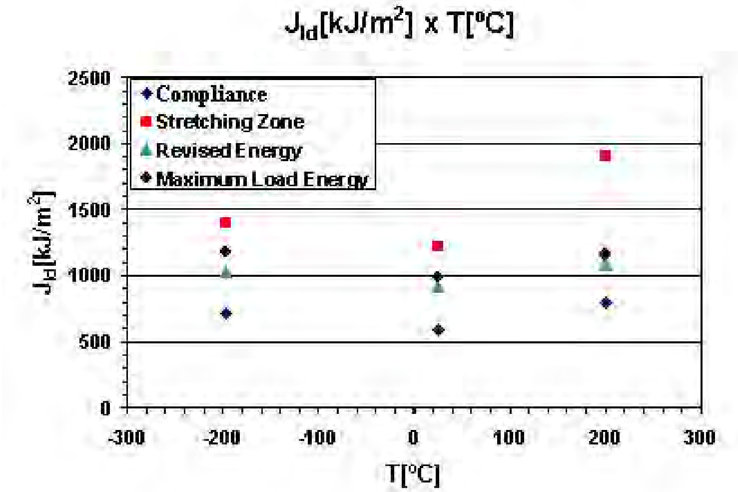

Figure 8. J_{Id} changing with temperature for different methods.

Table 6. J_{Id} changing with temperature for difference methods.

Method	$T_{-196ºC}$ J_{Id}[kJ/m2]	T_{room} J_{Id}[kJ/m2]	$T_{200ºC}$ J_{Id}[kJ/m2]
Compliance	712.86	586.00	797.43
Stretching Zone	1401.03	1213.29	1905.79
Revised Energy	1027.50	917.44	1087.68
Maximum Load Energy	1180.33	985.80	1155.68

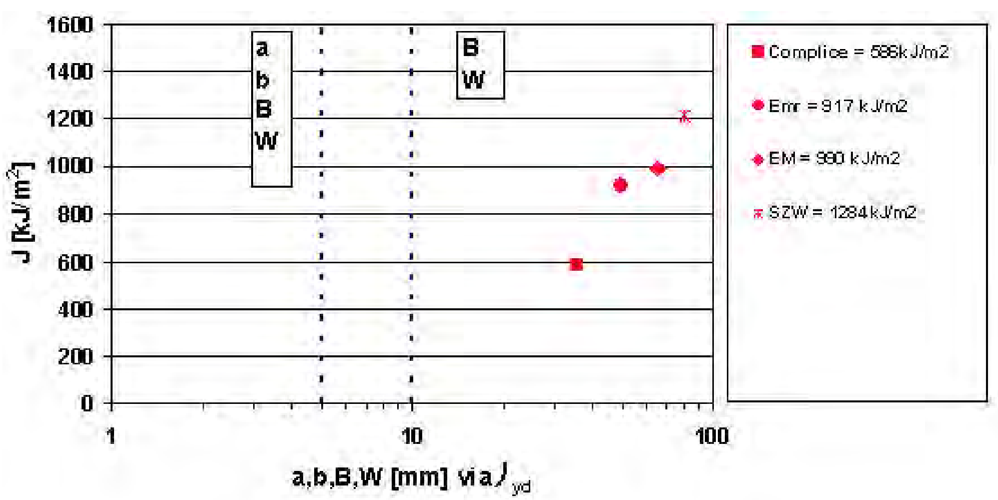

Figure 9: Validation region for toughness fracture at the room temperature.

CONCLUSIONS

The compliance changing rate method was more conservative than other methods.

The angle blunting (θ) values changed from 22º to 27º.

The fracture toughness of the stainless steel austenitic 316 changed from 712 to 1156 kJ/m^2 in the range temperature from −196 ºC to 200 ºC.

The stainless steel austenitic 316 showed ductile behavior in the range temperature from −196 ºC to 200 ºC.

All methods and material used in this work did not agree ASTM E1820 standard that indicates the plane strain was not occurred in the tip crack in AISI 316.

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