EVALUATION OF THE FATIGUE CRACK GROWTH OF AN ABNT 1016 HOT-ROLLING STEEL AND IN WELD METAL OBTAINED BY GMAW PROCESS

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Abstract. *The fatigue fracture is the most common type of structural failure and through the years it has been a challenging problem. It is caused by the initiation and propagation of a crack through the component, with the two processes occupying different proportions of fatigue life.*

The objectives of this research were the determination of the mathematical expressions for the rate of propagation of a crack by fatigue versus the stress-intensity factor range, in samples of an ABNT 1016 hot-rolling steel with thickness of 12 mm and in WELD cast steel area ABNT 1016 obtained for welding GMAW process.

The fracture analysis in scanning electron microscope obtained through the tensile test and Charpy showed that the lack of penetration in the weld metal changed the type of fracture from ductile to fragile. In the rolling condition, the evolution of energy versus the temperature showed anisotropy of this property and, in the rolling direction, the energy values were superior than the values obtained in the transverse direction.

The obtained results showed that on stage II, of the crack by fatigue propagation test, the material obeys the Paris law for appliance longitudinal direction. The evolution of the crack length, related to the number of cycles of the base metal and welding zone were compared and approximate to the obtained expressions by Lal et al, 1994. However, a linear correlation between the parameters C and m_f *was verified. This correlation between C and* m_f *doesn't exist when working with Bergner's model (Bergner, 2000). There was variation on the rate of propagation of a crack by fatigue on stage II, for thickness of 12 mm direction LT, analyzed according to Bergner's model and in welding steel area. In the same manner that, in the tensile test and Charpy, the presence of discontinuity changed the nature of the fraction and justify the variation in the rate of crack propagation.*

Keywords: *GMAW Process, Fatigue Crack Growth, ABNT 1016 Hot-Rolling Steel.*

1. INTRODUCTION

The ABNT 1016 steel is applied in metallic structures because it gives high mechanical resistance assisted to its low cost, good weldability and machinability. In the automotive industry, is used in welded joints by GMAW process, on the project developing phase - called "null phase" - which precedes the prototype building, as a mechanical system support structure like motopropulsor, suspension, conduit and exhaust. Therefore, the weldment resistance to the cyclical loads condition, which they are submitted, is required. This can take to the crack initiation and propagation with a posterior fatigue rupture, implicating the security of tests.

The fatigue can be defined as a phenomenon that occurs in components and structures submitted to cyclical extern loadings and it manifests in the deterioration of the material ability to tolerate the loading that was projected. The material fracture has its begin in cracks by gaps or incisions. Therefore, is important to identify the fatigue crack mechanism propagation, with intuit of improving the material characteristics.

For the biggest part of alloys in engineering, the curve *log (da/dN)* (*a*: crack size, *N*: cycles) *versus log* (ΔK) (ΔK: stress intensity factor range) exhibits a sigmoidal variation, as showed in Fig. 1. In that graph, we can observe the stages I, II and III, which the characteristics are:

• Stage I – the crack and the plastic deformation which surround the crack vertex are confined to some few grains, the crack growth occur predominantly by unique shearing on the direction of the primary sliding system; the medium increment by cycle is smaller than the space lattice and it associates to $\Delta K_{threshold}$ (intensity factor of threshold stress), below it doesn't occur the crack growing. In practical terms, $\Delta K_{threshold}$ is defined as the stress intensity cyclical factor, which its crack growth rate is equal to 10^{-8}mm/cycle.

• Stage II – occurs in ranges of higher stress intensity value; the plastic zone in the crack vertex incorporates many grains; crack growth process involves flow through two sliding systems; the crack grows through de progress of a fixed quantity by stress cycle; the microstructure and the loading conditions aren't very important at this stage.

• Stage III – corresponds to the final abrupt fracture that occur in the last stress cycle, when the progressively developed crack reaches the critical size for the shaky propagation and catastrophic failing; suffers a great influence of the microstructure and loading conditions.

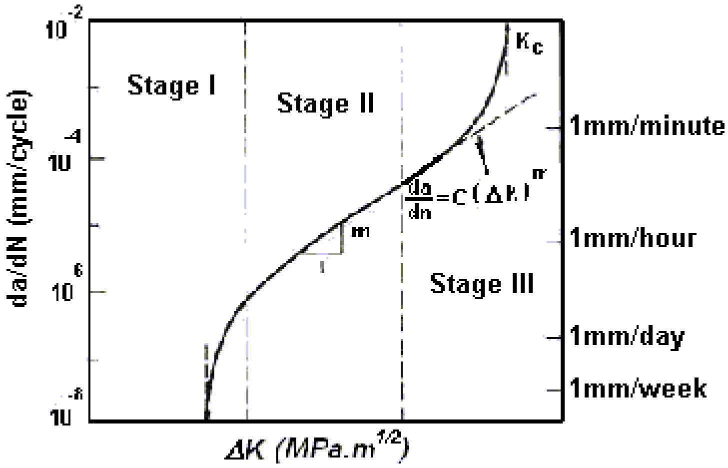


Figure 1 – Different stages in the fatigue crack propagation. Source: Suresh (Suresh, S. 1998)

For the constant loading amplitude, some models are prediction proposal of the fatigue crack propagation. They involve material constants, loading rates and operating stress level. The Paris & Erdogan (Paris, P.C.; Erdogan, 1963) model (Eq. 1) is an empiric relation that obeys to the strength law and describes the fatigue crack growth in the area II of the curve *da/dN* in function of ΔK, in which C and m are constants of the material experimentally determined.

$$\frac{da}{dN} = C(\Delta K)^m \quad (1)$$

Bergner & Zouhar (Bergner, F.; Zouhar, G, 2000) investigating the correlation existent between the coefficient and the exponent from the Paris model for different aluminum alloys suggested a new representation that obtains coefficients statistically independent (Eq. 2, 3, 4 and 5). This relation would be reached through the ΔK division by a factor of adequate scale ΔK_0. For the application of Bergner & Zouhar model, are necessary the minimum of 3 crack propagation tests, while in the Paris & Erdogan model it is necessary only one.

$$C_g = \left(\prod_{j=1,k} C_j \right)^{1/k} \quad (2)$$

$$\Delta K_p = 10 - \left[\frac{\sum_{J=1,\mathrm{K}} \left(m_j - \overline{m}\right) log\left(\frac{c_j}{c_g}\right)}{\sum_{j=1,\mathrm{K}} \left(m_j - \overline{m}\right)^2} \right] \quad (3)$$

$$\frac{da}{dN} = C_0 \left(\frac{\Delta K}{\Delta K_p} \right)^m \quad (4)$$

$$C_0 = C \Delta K_p^m \quad (5)$$

The objectives of this research were, the determination of the mathematical expressions for the rate of propagation of a crack by fatigue versus the stress-intensity factor range for the ABNT 1016 hot-rolling steel and in ABNT 1016 WELD METAL cast steel area, obtained for welding GMAW process, besides comparing the Paris & Erdogan and Bergener & Zouhar models for the stage II of crack propagation.

2. METHODOLOGY

The material used on this paper was: samples of ABNT 1016 hot-rolling steel with thickness of 12 mm, forthcoming by GERDAU AÇOMINAS GERAIS S/A.

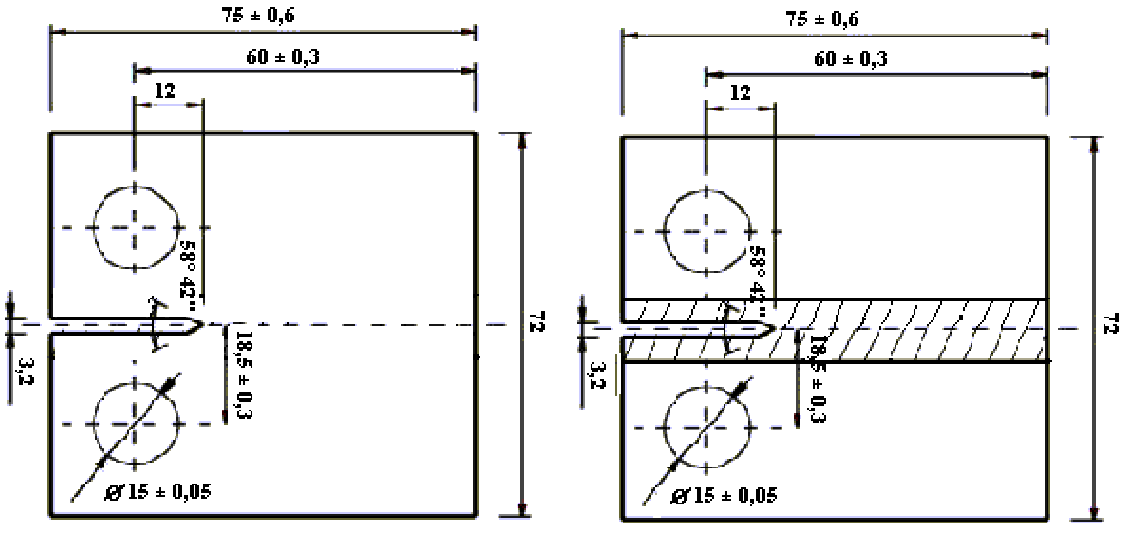
Table 1 – ABNT 1016 steel chemical composition.

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

For the test specimen welding, was used an automatized device for the process standardization, that controlled the length and the speed of the welding wire, beyond the stress in the beginning of the melting hole. The welding MAG process was realized in the plan/horizontal position, with an addition metal ER-70SG, tubular wire, flow gas in the proportion of CO_2 (15%) and Air (75%), direct current with positive polarity, in unique pass with V chamfers with clearance of 2.5mm and a joint aperture angle of 90º, following the project rule for the fusion welded joint (FIAT Project – 00920, 1983).

A tension test was made to obtain the mechanical properties (Miqueri, F.R.; 2006) following the ASTM E 8M (ASTM E 8M, 1995) rule. The equipment used was an INSTRON machine, model 4487 with an action servohydraulic and 100kN loading cell, and the values found were used in the crack propagation test. Six tension tests were made on the ABNT 1016 steel plate, according to the rolling direction, on the joint with chamfers 1V and ½V.

The test specimen for the fatigue crack propagation test, of the kind C(T), were made as the ASTM E 647-99 (ASTM E 647-99, 1999) rule, with a 12mm thickness and 75mm width. For the base metal, a TL direction was followed, while for the welded test specimen the propagation occurred parallel to the lamination direction (Fig. 2).



(a) (b)

Figure 2 – Traction-compact test specimen dimensions, of fatigue crack propagation, according to ASTM E 647-99 norm for the (a) base metal and (b) welded joint with incision in the welding zone.

The tests were realized at the ambient temperature in a universal servohydraulic INSTRON machine model 8802, compound of a dynamic system with the maximum capacity of 250kN, claw head block and hydraulic lifting with a maximum distance of 1515mm, load and position digital electronic controller, built in modular tower for 5 controller or data acquisition plates. Each acquisition system can accommodate until 8 additional transducer, digital electronic controller with PID automatic parameters modernization until 1kHz, signs digital processing with 19 bits resolution without the manual adjust or suppression necessity, conditioning of the high precision transducer, low noisy with variable filters from 0 until 1kHz. For the measuring of the crack size a clip gauge INSTRON model 2670-116 was used, with a fixed opening of 10mm and a variation of ±4mm. The reason of the R load adopted was 0.2, and the frequency, 20Hz. Were analyze three tests for the base metal and three for the welding zone. Fracture analyses were made on the broken test specimen in Scanning Electron Microscope, JEOL brand, gifted of EDS.

3. RESULTS AND DISCUSSION

The radiographic test in the test specimen with incisions 1V and ½V, for the welding quality verification, showed that the test specimen, presented discontinuities as cracks and lack of penetration on the welded joint, for plate thickness of 12mm.

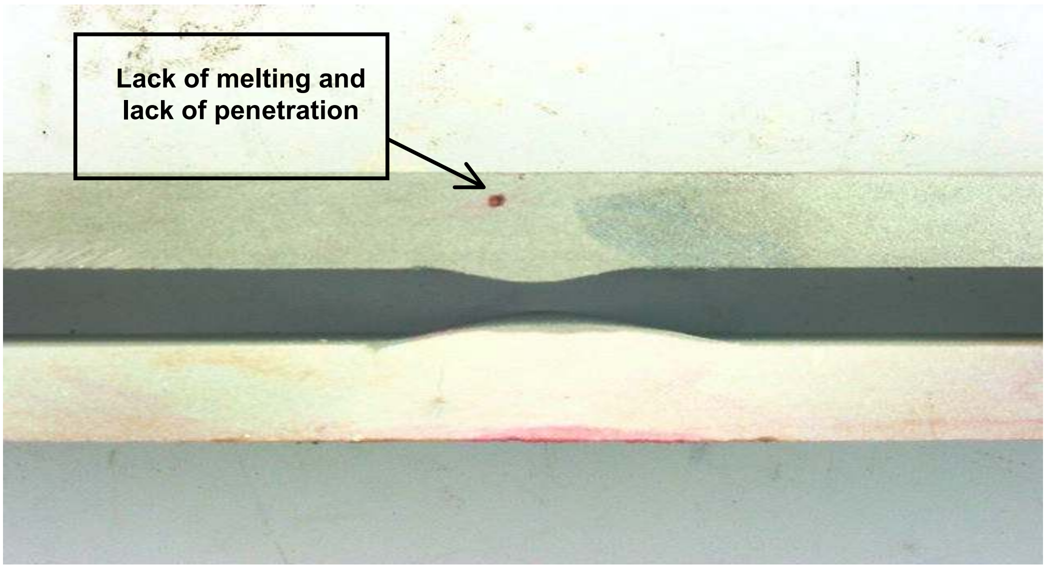


Figure 3 – Radiography on the joint, where the lack of melting and lack of penetration is observed. (½V incision).

The existence of these discontinuities observed in the radiography was confirmed, later, by the macrograph (Fig. 4).

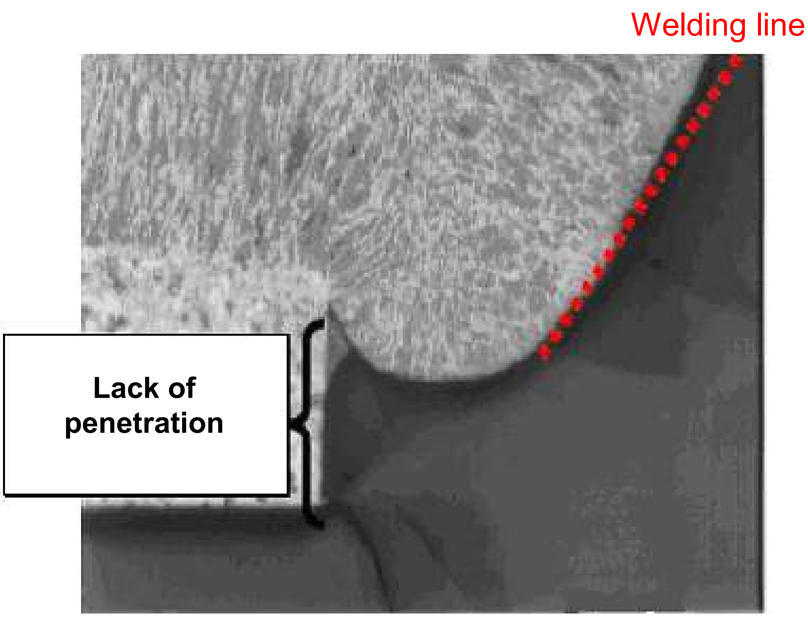


Figure 4 – Welded joint macrograph with ½V incision, where the lack of penetration in the welded junction on the base metal is observed. 10X increase.

The Table 2 presents the results of modulus of elasticity, yield point, endurance limit and stretch obtained in the tensile test.

Table 2 – Results of modulus of elasticity, yield point, endurance limit and stretch for the ABNT 1016 steel plate and the 1V e ½V welded joint.

Dimensions	Base Metal	1V	½V
Modulus of Elasticity (MPa)	116078.3	--------	-----------
Yield Point (MPa)	211.1 ± 11.6	205.3 ± 4.7	206.7 ± 8.8
Endurance Limit (MPa)	314.0 ± 14.0	318.1 ± 1.3	288.4 ± 36.9
Stretch (%)	60.4 ± 1.4	60.2 ± 2.6	43.3 ± 14.4

Fatigue crack propagation *da/dN* in function of ΔK curves were obtained for the base metal in the TL direction and for the welding zone. The Figure 4 shows the obtained graphs and the Table 3 the crack growth parameters C and m verified using the modeling composed by Paris & Erdogan (Eq. 1):

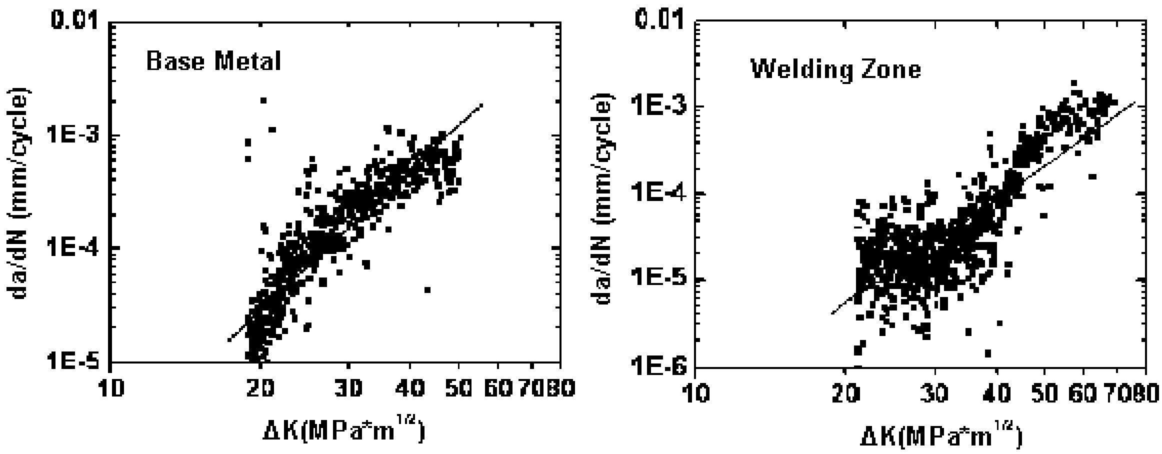


Figure 5 – The evolution of fatigue crack propagation curve *da/dN* X ΔK at the stage II for ABNT 1016 steel samples with thickness of 12mm, base metal in the TL direction and for the welding zone, obtained by welding GMAW process, tested with the loading relation R=0,2 and frequency 20Hz.

Table 3 – C and m stage II crack growth according to Paris & Erdogan model for ABNT 1016 steel samples with 12mm thickness base metal in the TL direction and for the welding zone, obtained by welding GMAW process, tested with the loading relation R=0,2 and frequency 20Hz.

	Base Metal		Welding Zone	
	C	m	C	m
	$7.58x10^{-9}$	3.01	$2.94x10^{-11}$	4.04
	$1.35x10^{-10}$	4.09	$1.26x10^{-11}$	4.39
	$2.06x10^{-11}$	4.64	$2.06x10^{-11}$	4.64
Media	$2.58X10^{-9}$	3.91	$2.09x10^{-11}$	4.36

The coefficients and exponents of ΔK found for the base metal are agreeing with the Lal (Lal, D.N.; 1994) consideration and disagreeing with Barsom and Rolfe (Rolfe, S.T.; Barsom, J. M., 1987) consideration for pearlite-ferrite steel. For the welding zone, the values found are agreeing with Martins (Martins, G. P., 2004) consideration. The values obtained for the base metal and for the welding zone doesn't permit a differentiation of the fatigue mechanisms obtained.

The correlation between the coefficient C and the exponent m from Paris model for the base metal and welding zone was verified. The obtained graph, illustrated in the Fig. 6, shows the existence of a linear correlation between the parameters of crack growth and a high correlation coefficient. This fact is justified by the algebraic structure of the equation with its logarithmic representation and by its non-dimensional homogeneities.

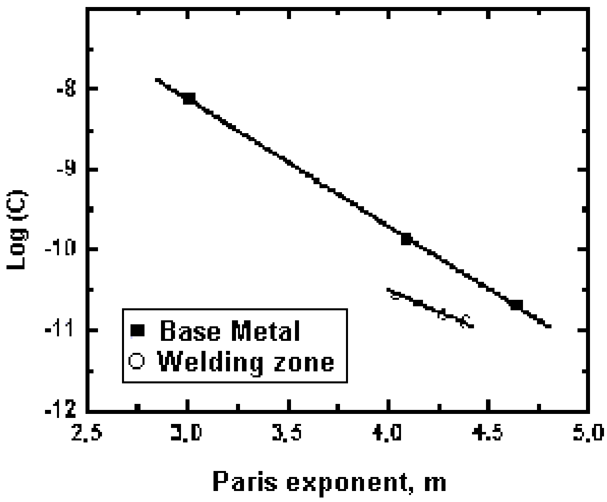


Figure 6 – Correlation graph between log (C) and m of the Paris & Erdogan equation for ABNT 1016 steel samples with thickness of 12mm, base metal in the TL direction and for the welding zone, obtained by welding GMAW process, tested with the loading relation R=0.2 and frequency 20Hz.

Table 4 – Correlation between the crack growth parameters C and m according to Paris & Erdogan model.

	Correlation equation	Correlation coefficient
Base Metal	log (C) = -3.38 –1.57m	-0.99
Welding Zone	log (C) = -6.21 –1.07m	-0.99

The Figure 7 presents the graph of the correlation between log (C_0) and m as the Bergner & Zouhar model for the base metal and for the welding zone. Is observed the absence of a linear correlation between the crack growth parameters C_0 and m.

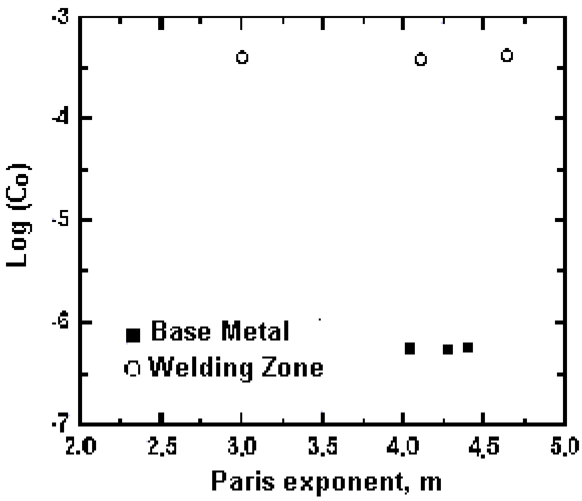
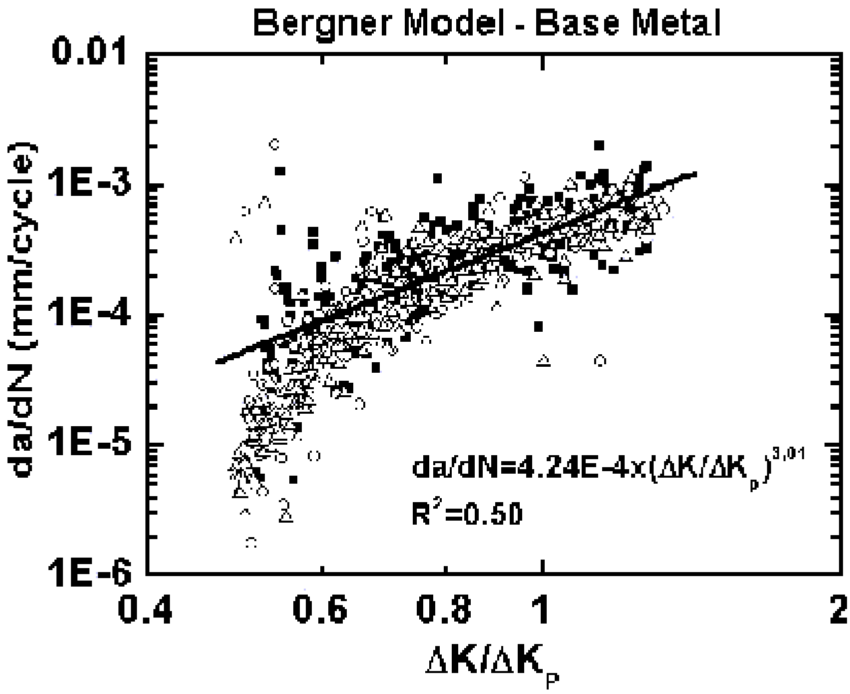


Figure 7 – Correlation graph between *log (C_0)* and m according to Bergner & Zouhar equation for ABNT 1016 steel samples with 12mm thickness, base metal in the TL direction and for the welding zone, obtained by welding GMAW process, tested with the loading relation R=0.2 and frequency 20Hz.

The graphs *da/dN* versus $\Delta K/\Delta K_p$ as the Bergner & Zouhar for the base metal and welding zone were obtained and represented in the Fig. 8. The fatigue crack growth parameters are represented in the Tab. 4, which was found that the difference in the crack growth rate between the hot-rolling ABNT 1016 and the welding zone after welding by the GMAW process is related to the presence of discontinuity of the welding joint.

The Figure 8 (a) and (b) shows the graphs *log* da/dN *versus* $\Delta K / \Delta K_p$, according to Bergner & Zouhar, for the test specimen of 12mm thickness in the TL direction in the base metal and welding zone, for the loading ratio $R = 0.2$. It was found originated in this graph the difference in the crack growth rate with the loading relation for the ABNT 1016 hot-rolling steel and for the welding zone after the welding by the welding GMAW process.



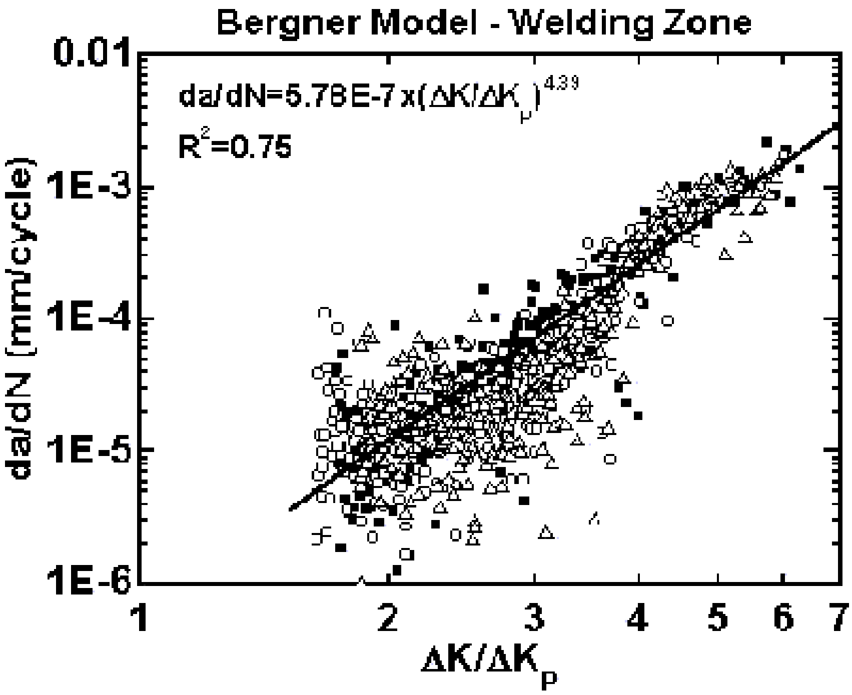


Figure 8 – Graphs da/dN versus $\Delta K / \Delta K_p$ according to Bergner & Zouhar, for the test specimen of 12mm thickness in the TL direction in the (a) base metal and (b) welding zone for the loading ratio $R = 0.2$

In the Figures 8 (a) and (b) is observed that the crack propagation, according to Bergner model is bigger in the base metal when compared with the crack propagation in the welding zone.

The Figure 9 evidences the microfractography of ABNT 1016 steel samples with 12mm, welding zone in the TL direction loading ratio R=0,2. It evidences the presence of the fatigue propagation area and cleavage in reason of the joint discontinuity presence. The presence of discontinuity changed the fracture type.

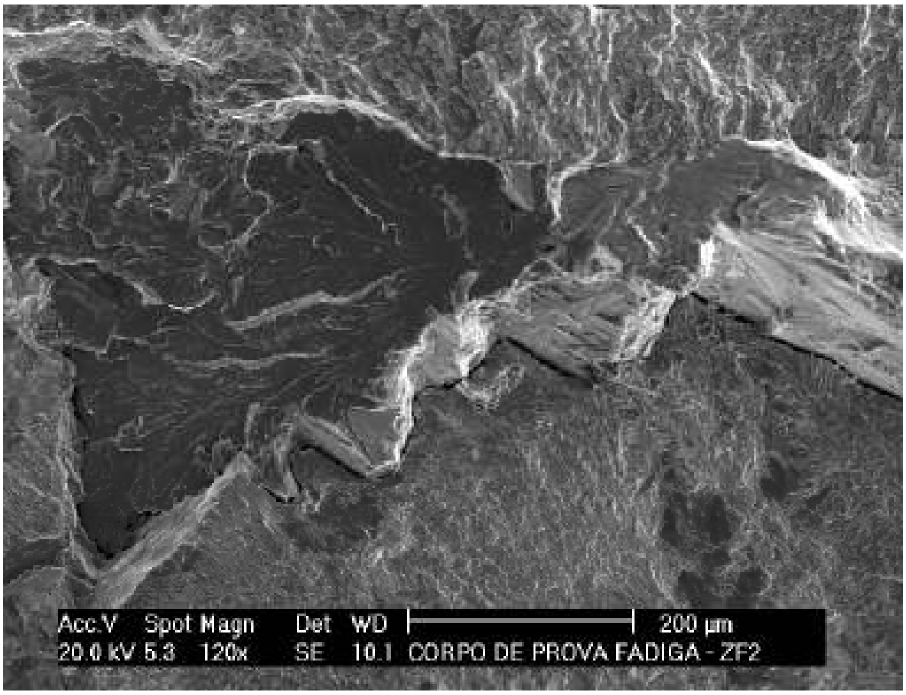


Figure 9 – Fractography of ABNT 1016 steel on the welding zone at the Scanning Electron Microscope with 12mm thickness, TL direction. Evidencing the cleavage area with the welding discontinuity.

4. CONCLUSION

- The coefficients C and m obtained from Paris & Erdogan model were approximated when compared with the base metal and welding zone, not permitting a differentiation of the mechanisms;
- There was a variation on the crack propagation on region II rate of the *da/dN* in function of ΔK curve, when analyzed by the Bergner & Zouhar model. This variation is caused by the discontinuity in the welding joint presence;
- The lack of melting presence affected the mechanical properties and changed the fracture aspect from ductile to fragile near to the discontinuity area.

5. ACKNOWLEDGMENTS

The authors thank Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG), and technicians Nirlando Antônio Rocha and Emil Reis.

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