NUMERIC AND EXPERIMENTAL COMPARISON OF FATIGUE CRACK GROWTH RATE IN WELDED VIRTUAL SPECIMENS

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Abstract. *The presence of welding residual stresses close to cracks in structures involves modifications in the field of stresses, when they are submitted to some loading effect. The modifications in the level of stresses obviously affect the structure with respect to its fatigue behavior. This work develops computational simulations for determination of the crack growth rate of the soft martensitic stainless steel CA6NM, material commonly used in the manufacturing of hydraulic turbines, in homogenous and as welded conditions. The objective of this work is to evaluate the influence of the field of welding residual stresses or the error due to the lack of this field in the computational results. For this purpose, it is considered the existence of experimental data in CT specimens for determination of the fatigue crack growth rate with this alloy, according to the ASTM E647-95 standard. The finite element method is used for stress evaluation and the experimental results serve to calibrate the simulation in virtual geometric CT specimens. It is verified that the results are in agreement with the theory; the numerical values are lower than the experimental ones, because the field of residual stresses are absent in the computations, showing the maximum error when the pre-crack is at the heat affected zone (average of 67%) if compared to the weld metal region (average of 21%), local where probably traction residual stresses are higher (heat affected zone).*
Keywords: *fatigue, finite element method, CT specimen, virtual test, residual stress.*

1. INTRODUCTION

The activities to be realized in this line of research are related to the study of the fatigue crack propagation, where the influence of the residual stresses, geometrical distortions, plastic deformations and changes of microstructure are important in the fatigue treatment of welded structures with cracks. As the experimental tests are time-consuming and involve extra expenses, it would be interesting to simulate cracked welded structures for computational determination of the crack growth behavior. However, the validation of the simulation needs certain experimental results, some already found in previous research.

A posterior application, for example, would be to evaluate the required stresses for fatigue crack propagation in hydraulics turbines, observing that cracks can be found in the welded unions of the blades in the rotors or in cavitated areas repaired by welding. Then, it is important to know how the structure strengths the fatigue crack propagation, in order to program with better criteria the repair/maintenance of these turbines.

For initial validation of the methodology to be used, the research uses the geometry of homogeneous test specimen, similar to the test specimens for experimental determination of the fatigue crack propagation. Next, geometries of welded specimens are used, where the properties of the weld metal and the heat affected zone (HAZ) are properly considered. The work evaluates the relative error obtained in the simulation without consideration of the field of residual stresses.

In detail, the objectives of this research involve:

To evaluate how the residual stresses and microstructural changes, generated by welding and probably by thermal treatment, influence in the fracture strength and consequently in the fatigue crack growth of welded joints.

As the fracture and fatigue are dependent on the material, one second objective is to evaluate the variables that influence in crack propagation of welded joints of the CA6NM alloy.

In this context, the specific objectives of this work involve the bi-dimensional modeling of CT specimens, for crack growth evaluation, and its comparison with experimental results obtained by Pukasiewicz[1]. Therefore, this work is based on CT specimens, homogeneous and as welded without thermal treatment, but they orient posterior work in 3D specimens and in more complex geometries.

2. THEORETICAL BACKGROUND

Fatigue is a process dominated by local deformation; therefore damage by fatigue can occur on levels of stress smaller than the yield strength of the material. In general, failures by fatigue initiate in regions of high stress concentration as non metallic inclusions, small geometric radius or preexisting defects[3].

The Linear Elastic Fracture Mechanics (LEFM) is an analytical method that correlates the magnitude and distribution of stresses in the neighborhood of cracks as consequence of applied loads at the structure considering the size, geometry and orientation of cracks; and determining the critical conditions for growing of cracks as function of the mechanical properties of the material.

The Stress Intensity Factor (K) characterizes the intensity of stresses in the neighborhood of the crack tip in an isotropic linear elastic material. Similar concepts can also be used to determine the rate of crack growth for fatigue, da/dN, in terms of the range of K in the crack tip, ΔK.

Generally it is convenient to express K by the Equation (1):

$$K = YS\sqrt{\pi a} \tag{1}$$

where Y depends on the geometry of the specimen, S is the applied stress and a is the crack length. Being w the width of the specimen, the compliance function Y is defined for the CT specimen by the Equation (2):

$$K = 1{,}12 - 0{,}231\left(\frac{a}{w}\right) + 10{,}55\left(\frac{a}{w}\right)^2 - 21{,}72\left(\frac{a}{w}\right)^3 + 30{,}30\left(\frac{a}{w}\right)^4 \tag{2}$$

In general, plastic strain in wide scale invalidates the application of the LEFM, remembering than the application of the LEFM is valid only for a linear relation between load, length of crack and displacement, and when the plastic deformed region is small in comparison with the geometrical dimensions of the structure.

For cyclic loading, when the crack suffers an increment Δa in its length because of an application of a number of cycles ΔN, the rate of growth for cycle is defined by the $\Delta a/\Delta N$ ratio, or for an infinitesimal interval through its derivative da/dN. The rate of crack growth by fatigue is, therefore, the angular coefficient of the straight line in the graph a versus N.

One main variable involved in the fatigue crack growth is the range of the stress intensity factor ΔK that depends on the geometric factor Y, the range of stresses ΔS and the length of the crack a, as given by the Equation (3):

$$\Delta K = Y\,\Delta S\sqrt{\pi a} \tag{3}$$

One relation for the rate of crack growth and the range of the stress intensity factor is given by the Law of Paris, through the Equation (4):

$$\frac{da}{dN} = C(\Delta K)^m \tag{4}$$

where C and m are constant characteristics for each material.

3. NUMERIC METHODOLOGY FOR FATIGUE ANALYSIS

The MSC.Patran™ program is used for creation of the geometric model; attribution of the properties, boundary conditions and loading; generation of the mesh; and, analysis of results (post-processing). The solution of the problem is done with the MSC.Nastran™ finite element program and posterior fatigue analysis with the MSC.Fatigue™ program.

Based on data supplied by Pukasiewicz[1], where tests in homogeneous and welded specimens had been realized, it was created a model of the CT specimen, firstly homogeneous and next as welded. Table (1) shows the mechanical properties of the steel CA6NM.

Table 1. Mechanical properties of steel CA6NM, in the quenched condition at 1050°C in air, and tempered at 590°C - 2h.

Tensile Strength (MPa)	Yield strength (MPa)	Hardness ($HV_{0,4}$)
800	670	266

Table (2) shows the experimental data considered for each part in our simulations, based on works of Pukasiewicz[1] at more and Novicki[2] for the HAZ mechanical properties.

Table 2. Mechanical properties of the welded joint

Property	Parent metal (PM)	Weld metal (WM)	HAZ (HAZ 01 specimen)
Yield strength (σ_{YS}) or flux stress (σ_Y)**, MPa	735**	891	891*
Ultimate tensile strength (σ_{ts}), MPa	800	1116	1116*
Load ratio ($R=P_{min}/P_{max}$)	0.1	0.1	0.1
Paris Law coefficient (C), m/cycle	1.224e-11	2.47e-13	7.837e-14
Paris Law exponent (m)	2.63	3.8	3.82

* Assumed equal to WM according to BS7910:1999 suggestion in a joint with mismatch properties, equal to part with upper values (WM).

** $\sigma_Y = \left(\frac{\sigma_{0,2} + \sigma_{ts}}{2}\right)$

Below the steps followed for the modeling:

- Creation of the 2D geometric model for the CT specimen, as shown in Figure (1), based on dimensions reported by Pukasiewicz[1];
- Attribution of the mechanical properties of each part of the structure;
- Determination of the type of element to be created;
- Modeling of the boundary conditions considering that the lower pin is fixed, whereas the upper pin applies a controlled load. For this reason, two half cylindrical geometries were inserted inside the holes, with superior elastic modulus value (2e13 Pa if compared to 2e11 Pa of the specimen), taking of care the pins do not deform the specimen. This makes that the numerical model is similar to the real one;
- Generation of the mesh, Figures (2) and (3);
- Solution of the problem;
- Calculation of crack propagation by the method da/dN x ΔK;

- For the heterogeneous model the mechanical properties of the welded and the HAZ regions were considered. The steps are similar to the homogeneous specimen one, however the mechanical properties of the weld metal AWR E410NiMo (in the welded condition) and those of the HAZ region had been incorporated.

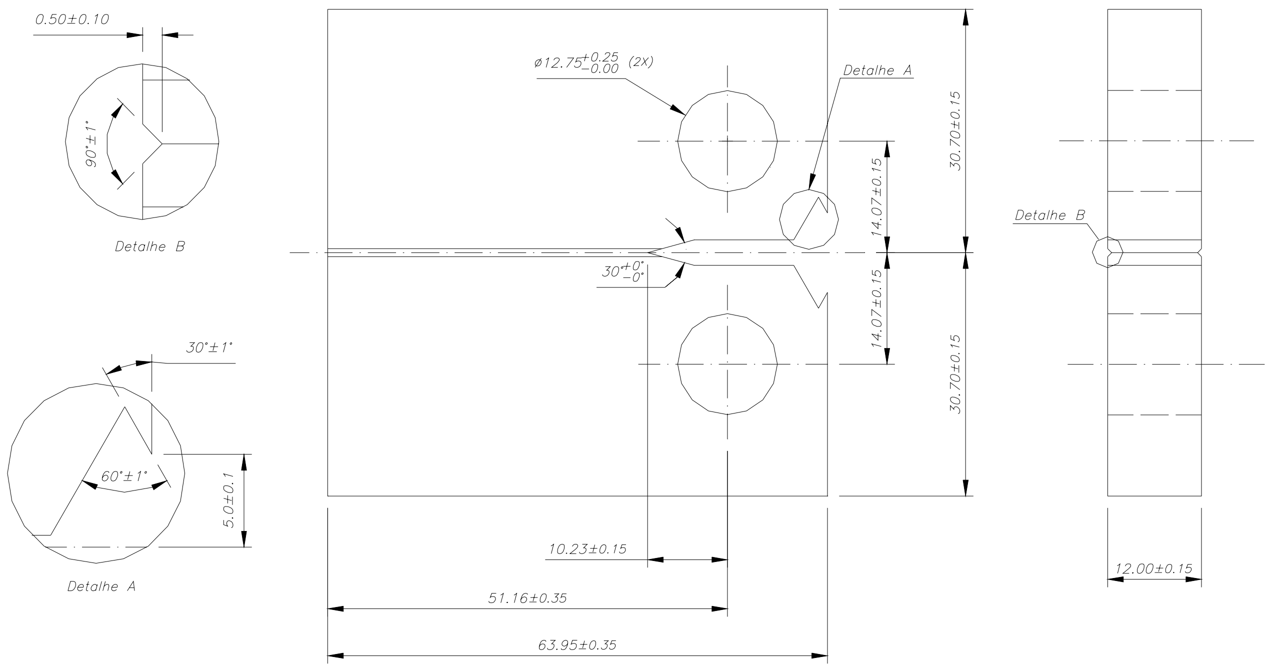

Figure 1. Dimensions in mm of the compact tension CT specimen, Pukasiewicz[1].

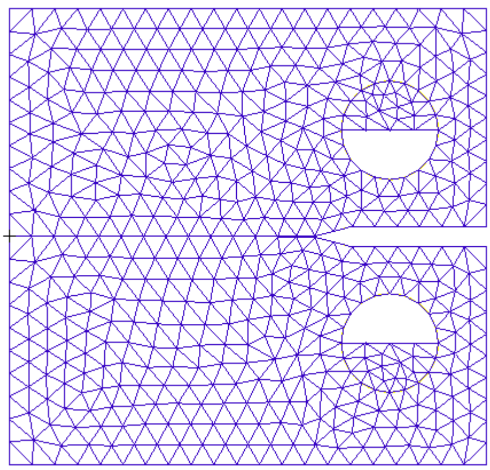

Figure 2. Mesh of the homogeneous specimen.

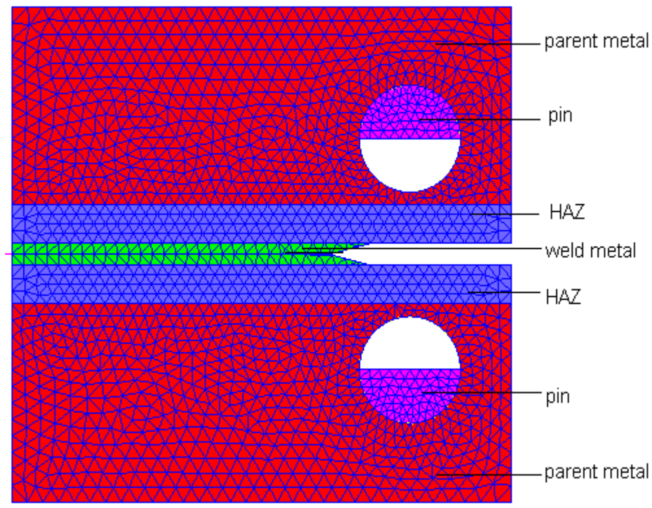

Figure 3. Mesh of the heterogeneous specimen.

There is an interaction between the welding residual stresses and the applied loads, modifying the nominal stresses effectively transmitted to the specimen. This interaction[4] is illustrated in Figure (4). As result of this interaction, an alteration of the rate $R=\sigma_{min}/\sigma_{max}$ is observed in the welded joint, basically in the zone where residual stresses of traction occur. In terms of behavior to the fatigue of the joint, these residual stresses are particularly relevant. In this work, that difference can be nominally evaluated.

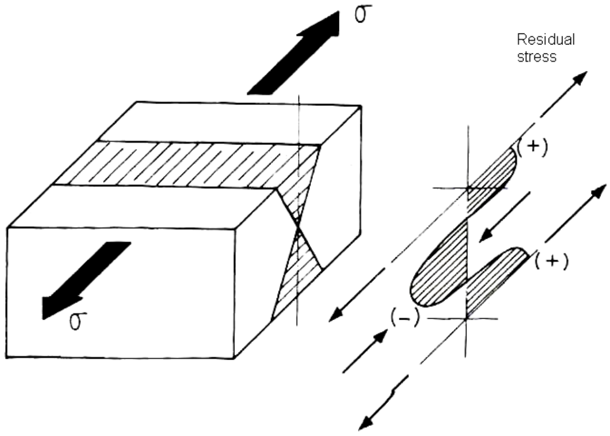

Figure 4. Interaction between applied loads and residual stresses at the welded joint.

4. RESULTS ANALYSIS

Fatigue numerical results are compared with experimental results obtained previously by Pukasiewicz[1], Figure (5). Two types of specimens were simulated, one CT specimen with homogeneous material and another one as welded, with consideration of the heat affected zone (HAZ). These simulations consider the mechanical properties of the weld metal and the HAZ, without the influence of the field of residual stresses by welding. Thus, it is possible to evaluate the contribution of the residual stresses during the fatigue crack propagation.

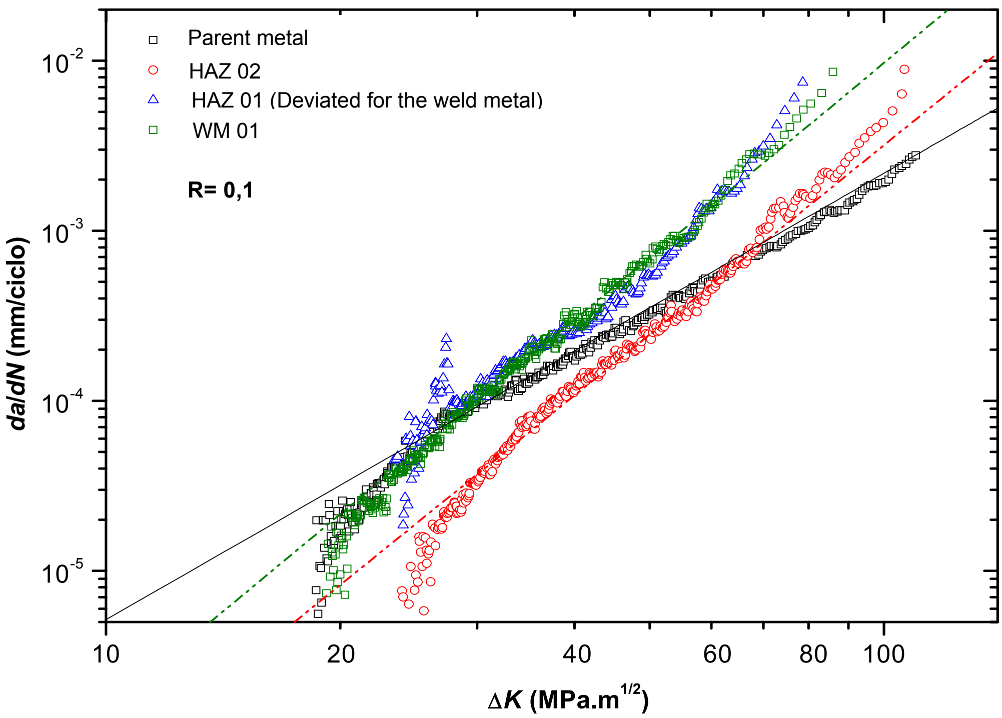

Figure 5. Fatigue crack growth rate for the steel CA6NM in homogenous and as welded CT specimens for different positions of the fatigue pre-crack, Pukasiewicz[1].

The computational fatigue crack growth curves for the three cases are shown in Figures (6) to (8).

Table (3) shows a comparison of the cracking values obtained numerically with those obtained by experimentation. The values of reference for the calculation of the relative error are the experimental ones.

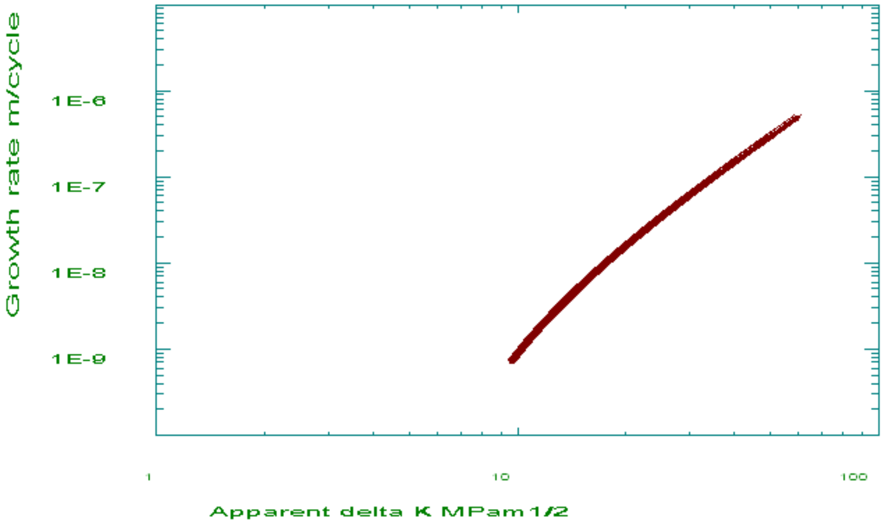

Figure 6. Fatigue crack growth rate with pre-crack at parent metal.

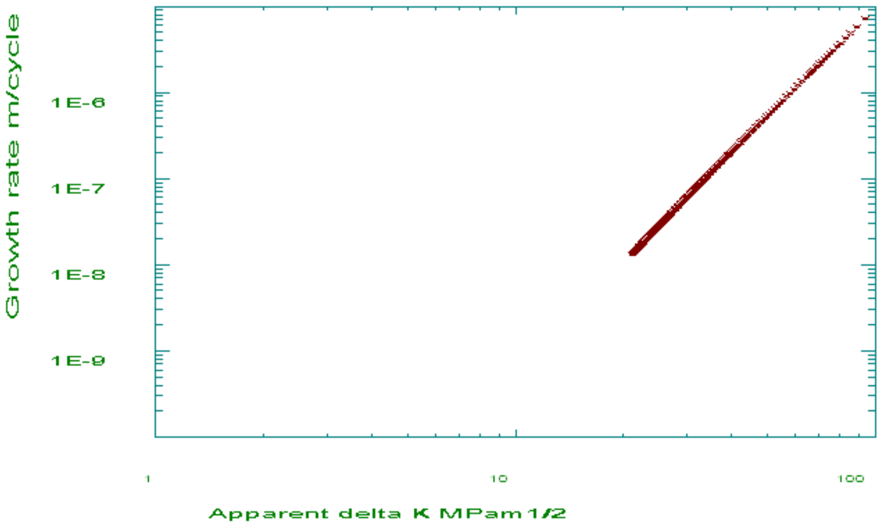

Figure 7. Fatigue crack growth rate with pre-crack at weld metal.

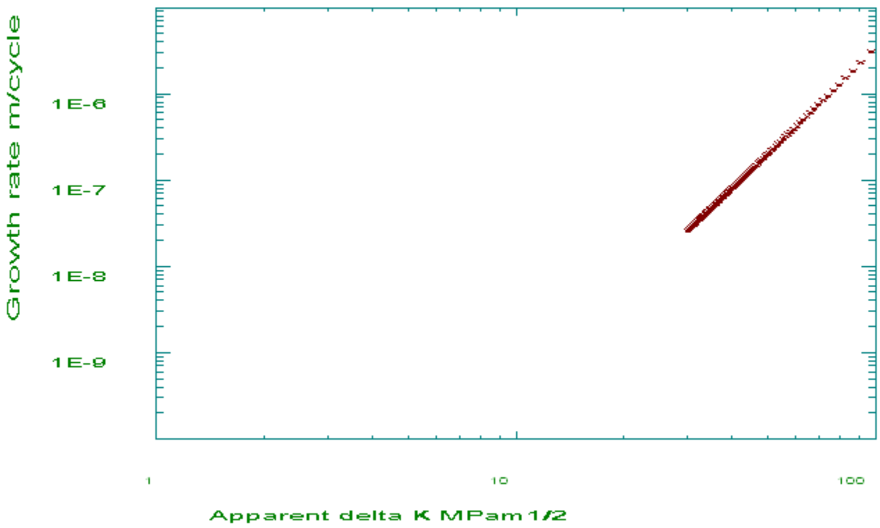

Figure 8. Fatigue crack growth rate with pre-crack at HAZ.

Table 3. Numerical error values of *da/dN* for some values of ΔK

ΔK	*da/dN* (m/cycle)								
	Homogeneous specimen			Pre-crack at weld metal			Pre-crack at HAZ		
(MPa.√m)	experimental	simulation	error	experimental	simulation	error	experimental	simulation	error
20	3,0E-08	2,0E-08	-33%	1,5E-08	1,2E-08	-20%	…	...	...
30	1,0E-07	8,0E-08	-20%	1,0E-07	8,0E-08	-20%	1,0E-07	3,0E-08	-70%
40	2,0E-07	1,8E-07	-10%	3,0E-07	2,5E-07	-17%	3,0E-07	1,0E-07	-67%
50	4,0E-07	3,5E-07	-12%	6,0E-07	6,0E-07	0%	6,0E-07	3,0E-07	-50%
60	6,0E-07	5,5E-07	-8,3%	1,5E-06	1,2E-06	-20%	1,5E-06	5,0E-07	-67%
70	8,0E-07	…	…	3,0E-06	2,5E-06	-17%	3,0E-06	1,0E-06	-67%
80	1,0E-06	…	…	6,0E-06	4,5E-06	-25%	9,0E-06	1,5E-06	-83%
90	1,5E-06	…	…	1,0E-05	7,0E-06	-30%	…	2,5E-06	…

It can be verified that the results are in agreement with the theory; the numerical values are lower than the experimental ones, because the field of residual stresses are absent in the computations, showing the upper error when the pre-crack is in the HAZ local (average of 67%) if compared to the weld metal (average of 21%), local where probably traction residual stresses are higher (HAZ). Obviously, as can be seen in Figure (4), the residual stresses will help the severity of applied loads in the specimen, making the crack grows faster.

5. CONCLUSIONS

The results demonstrate the error level when the welded structures are simulated without consideration of the residual stresses field, proving the importance of tools for evaluating this field. Although computational tools are economically advantageous if compared with experimental tests, it must be remembered the limitations of the simulation, the type and time of familiarization of the operator with the software, and the phase of validation of results. When the pre-crack is located at the heat affected zone, the numerical errors are higher if compared when the pre-crack is at the weld metal zone, meaning the great influence of residual stresses at the heat affected zone in this case.

6. ACKNOWLEGMENTS

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7. REFERENCES

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