

Numerical modeling of the welding defect influence on fatigue life of the weld bead with analyzing residual stress effects

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ABSTRACT - The main objective of this work is to modeling the effect of welding defects on the fatigue strength of the weld bead with taking residual stresses into account. Throughout this paper, we will present in the first part two principal approaches to predicting the stress concentration effects on the fatigue life duration, calculation methods based on each approach will be analyzed at the end of this part to determine the limitations and conditions of using each method. In the second part of this paper, we present our model based on the volumetric method to predict the fatigue life in the presence of defect in the surface of the weld bead. In the defect vicinity, the stress field distribution will be obtained with an elastoplastic material behavior, this distribution will be operated thereafter in a comparative study by introducing residual stress to illustrate the effect of the presence of these stresses on the fatigue life calculated with volumetric method.

KEYWORDS - Nonlinear modeling, notch reduction factor, residual stress, volumetric method, welding defect

I. INTRODUCTION

During their life cycle, metallic structures are subjected to cyclic loads with significant frequency, this significantly reduces the fatigue life of the components such as railroad lines and bridges. On structures subjected to static loads, welding defect is tolerated below a limit size [1]. In the case of cyclic loading, the defect is unacceptable, these discontinuities are an area of stress concentration producing crack nucleation which can spread out to the full fracture. New techniques for non-destructive testing is used to obtain critical information about the defect location and the geometric parameters, determining the defect influence on the fatigue life of the weld provide an answer on the impact of each defect detected and also provide criteria to accept defects in case of impact that will not change the desired performance of the weld.

II. MECHANICAL FATIGUE AND APPROACHES TO PREDICT LIFE DURATION UNDER CYCLIC LOADING

Evaluating the influence of welding defect on the fatigue strength can be done by considering à problem of fatigue in the presence of stress concentration. These coupled problem present difficulties to estimate the life duration, calculating this value by conventional method give different results compared with experimentations [6]. In the literature, there are many models based on approaches developed from observations of experimental results. We note at this stage that the calculation models developed from these approaches are limited to specific loading conditions that must be checked before. The fatigue life of a mechanical element cannot be evaluated by a single approach since it is divided into two main phases, the first phase is more significant [2] called fatigue life that begins with the non cracked state of the material and ends with the appearance of micro crack in the order of 1mm, this duration is analyzed with mechanical fatigue tools (S-N curve).The second phase is analyzed with linear fracture mechanics tools which allow finding the required number of cycle before failure by considering the initial parameters of the micro crack and loading intensity. This article will discuss the problem of welding defects analyzed with fatigue tools to calculate the predominant part of weld bead life.

a. Stress concentration effect on fatigue life

Using the maximum stress obtained by the stress concentration factor on the Wöhler curve to predict the fatigue life of notched components does not provide same results as that obtained experimentally, a new physical value called effective stress was introduced, it is this calculated stress that allow to predicts the fatigue strength by comparing it to the strength limit of the material [2] [3]. Effective stress replacing the maximum stress is calculated based on the distribution of the stress field in the notch vicinity, Similarly to determination the maximum stress by stress concentration factor (K_t), determination of the effective stress can be done by calculating the (K_f) factor, called fatigue reduction factor which is expressed by the ratio between the two loading generating same life duration (N) [3]:

$$K_f = \frac{\sigma_l}{\sigma_e} \tag{1}$$

Where (σ_l) is the nominal load applied on a smooth specimen and resulting (N) cycle to fatigue failure, and (σ_e) the nominal load applied on the notched specimen generating the same number of cycle (N) to fatigue failure. In general, the fatigue reduction factor is less than the stress concentration factor and the relationship between these two factors is expressed by the sensitivity factor q [3].

$$q = \frac{K_f - 1}{K_t - 1} \tag{2}$$

b. Approaches based on the notch effect in the prediction of the fatigue lifetime

The models based on this approach consider that the decrease in life time caused by notch depending on geometric parameters of the notch, these models are developed from experimental results that show an effect of reinforcement provided by notch under cyclic loading, this give a value of Kf lower than the coefficient of static stress concentration Kt. the calculation of Kf can be done by considering the nominal applied load and stress at a particular point in the vicinity of the notch or average stress observed in reinforced area.

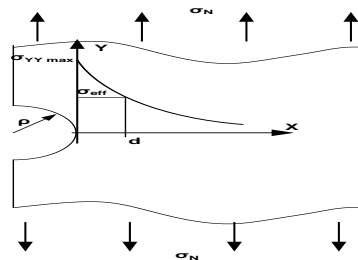


Figure .1. Notch geometry and load applied

Neuber’s Model [4] :

fatigue Life duration obtained experimentally is greater than that obtained by considering the maximum stress observed, Neuber justify this observation by the micro-support effect, this effect was described by calculating the average stress on reinforced area on very short distance (micro-support length ρ^*) in the vicinity of circular notch with radius ρ .

The average stress can be calculated by integration where the quantity ρ^* is known. In order to avoid the analytical integral calculus, Neuber has developed a direct method of calculation to determine a fictitious notch radius (ρ_f), the maximum stress at this fictitious notch is exactly the same as the average stress. Expression of the (ρ_f) is given by equation (3), where (ρ) is the notch radius and (s) is the micro-support factor:

$$\rho_f = \rho + s\rho^* \tag{3}$$

Therefore, determination of the fatigue strength requires the two factors s and ρ^* . A large number of experimental work show that the extent of the micro-support area ρ^* is closely related to the material properties (yield strength $\sigma_{Y0,2}$), while the factor s is related to the geometry of the notch (the notch of radius ρ , and the opening angle α) (figure 2).

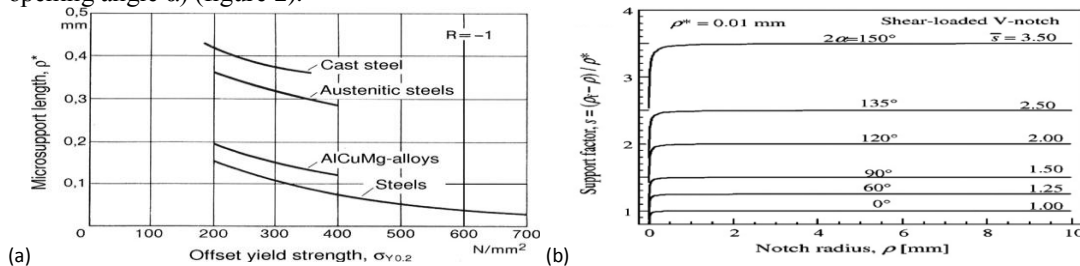


Figure. 2.

(a) : Evolution of micro-support distance as function of the material properties

(b) : Evolution of support factor as function of notch geometric properties

Another form of these results [5] joins the fatigue reduction factor K_f in relation with the stress concentration factor, material properties and the notch radius:

$$K_f = 1 + \frac{K_t - 1}{1 + \sqrt{\frac{a_n}{\rho}}} \quad (4)$$

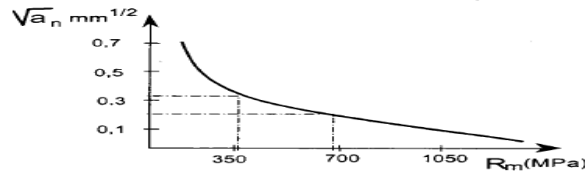


Figure.3. Neuber factor as function of tensile strength

Where (a_n) is the coefficient that depend of the material behavior and (K_t) is the stress concentration factor.

Peterson model [5] :

In developing his model, Peterson suggest that the stress that affect the fatigue life is located in a point away from a notch tip with distance (d) , this distance is characterized by the fact that the fatigue fracture appears when the stress at this distance exceed the endurance limit of the material.

$$\sigma_{yy}(d, 0) = \sigma_D \quad (5)$$

Area between the notch tip and point at the distance (d) can be assimilated as a reinforcement area discussed before in the Neuber's Model, this area can resist to the crack nucleation even if the stress at the notch tip exceed the endurance limit, PETERSON consider that the nature of the material has a large influence on the extent of this area. We note that the expression of the stress reduction factor developed in this model is obtained by considering the assumption of a perfectly linear material behavior, this expression is given as a function of the geometrical parameter of the notch but also depending on the material and the stress concentration coefficient.

$$K_f = 1 + \frac{K_t - 1}{1 + \left(\frac{a_p}{\rho}\right)} \quad (6)$$

Where (K_t) is the stress concentration factor, (a_p) is the parameter characterizing the material and (ρ) the notch radius, The K_t value can be deduced by finite element method whereas the (a_p) coefficient may be obtained by the following expression using ultimate tensile strength (R_m) :

$$a_p = \left(\frac{270}{R_m}\right)^{1,8} \quad (7)$$

c. Approach based on the gradient effect - Volumetric method

Gradient effect:

The recent development in fatigue calculation (stress field intensity method, volumetric method ...) was motivated by experimental results showed that the fatigue life is not influenced by the presence or absence of a geometric notch, but a more general effect which can be summarized in the variations of stress in the notch vicinity in the area of crack initiation, the effect of the stress variation on the fatigue life is known as the gradient effect. Experimental work of Palin-Luc [6] showed the effect of the gradient, they were carried out on smooth fatigue specimens (Figure-4), a part of these test specimens were subjected to cyclic tensile stresses, another family to rotating bending load. The tests are conducted to find the endurance limit in each case by imposing the number of cycles to failure (between 10^6 and 10^7). The results obtained by Palin-Luc are grouped for different materials in Table-1.

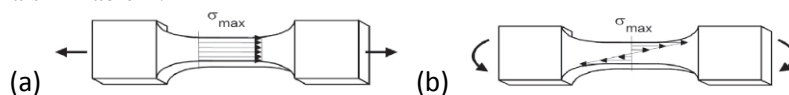


Figure .4.

(a) : Tensile-compressive fatigue load

(b) : Rotating-bending fatigue load

Table 1: Experimental results under tensile-compression and rotating bending load.

Alloy	Endurance limit in tension compression σ -1 (MPa)	Endurance limit in rotating bending f-1 (MPa)	Proportional variation between σ -1 and f-1 (%)
Steel 30NCD16	560	658	17,5
Cast iron XC18	273	310	13,6
Cast iron GS61	245	280	14,3
Steel 35CD4	558	581	4,1

These results are obtained on smooth test specimen with identical geometry and were subjected to the same maximum tensile stress, it can be concluded from this results the influence of stress variation created by bending load on the fatigue life.

Volumetric method [10]:

The volumetric method is based on the relative stress gradient (χ) to calculate the fatigue reduction factor Kf, Calculus start with a particular finite element analysis to determine the elastic-plastic stress field near the notch tip, the numerical results of this analysis are used to obtain the evolution of the stress gradient. The Kf factor is calculated as the ratio between the average effective stress (σ_{eff}) and the nominal load applied (σ_n), the effective stress is calculated by integrating the opening stress multiplied by weight function, the integration area is limited in a cylindrical volume, the diameter of the volume is located between the notch tip and the point where the relative stress gradient is minimum.

$$\chi(x) = \frac{1}{\sigma_{yy}(x)} \frac{d\sigma_{yy}(x)}{dx} \quad \text{Stress relative gradient} \quad (8)$$

$$\phi(x) = 1 - x\chi(x) \quad \text{Weight function} \quad (9)$$

$$\sigma_{eff} = \frac{1}{X_{eff}} \int_0^{X_{eff}} \sigma_{yy}(x) [1 - x\chi(x)] dx \quad \text{Effective stress} \quad (10)$$

Fatigue reduction factor can be calculated as below:

$$K_f = \frac{1}{\sigma_n X_{eff}} \int_0^{X_{eff}} \sigma_{yy}(x) [1 - x\chi(x)] dx \quad (11)$$

Where (X_{eff}) is the extent of the fatigue process area, $\sigma_{yy}(x)$ is the crack opening stress.

III. MODELING THE INFLUENCE OF THE DEFECT ON FATIGUE LIFE IN THE PRESENCE OF RESIDUAL STRESSES.

In this section, we will carry out a model to estimate the impact of the porosity defects on the fatigue strength of a weld bead with residual stresses. This defect is modeled by a semi-spherical discontinuity, the influence of this singularity on the fatigue strength will be carried out by calculating the fatigue reduction factor (Kf). This influence will be studied by determining (Kf) in the presence and absence of residual stress to illustrate the impact of these stresses on the fatigue strength of the weld bead.

a. Geometric description of analyzed model

The considered model is a butt welding of two plates. The thickness of the plates is 6 mm and the width of the weld bead is set equal to 10mm. porosity defect is present on the surface of the weld, the radius is set to 1 mm (Figure-5).

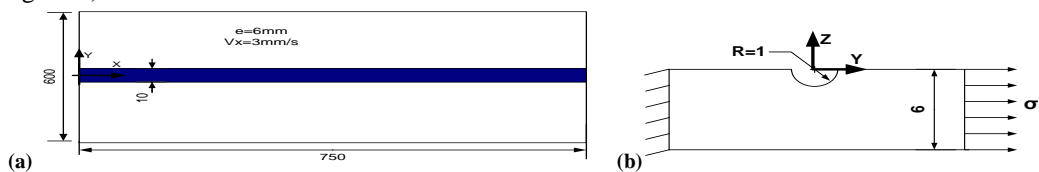


Figure.5.:

- (a) Overview of the surface of the two plates
 (b): Local geometry of weld defect and direction of applied load

b. Numerical finite element analysis of the stress field due to the applied load Mechanical properties of the material:

The material used is a structural steel [8], the stress field analysis will be conducted by ANSYS code by adopting an elastic-plastic material behavior [12], that due to the opening stress (σ_{yy}) intensification at the notch tip and the presence of residual stresses.

Table 2: mechanical Properties of the used material

Mechanical proprieties			Parameters of Ludwik model	
Yield strenght Re (MPa)	Tensile strength Rm (MPa)	YOUNG modulus E (GPa)	Hardening exponent n'	Hardening Coefficient K'
312	500	186	0,163	1053 MPa

The mechanical properties of the material are listed in Table-2. These parameters will be used to plot the material behavior under tensile stress by the following expression to approach the plastic behavior in the nonlinear area:

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'} \right)^{\frac{1}{n'}} = \frac{\sigma}{186 \times 10^3} + \left(\frac{\sigma}{1053} \right)^{\frac{1}{0.163}} \quad (12)$$

Load application and numerical solution:

After building the model geometry and defining the material properties, the geometry is meshed with refining the size of the elements near the notch tip, the area on which our study is focused requires a good accuracy of the stress results, these values constituting the main data to determine the (Kf) by the volumetric approach. The applied load will be a tensile load (σ) of 150 MPa applied along the (Y) axis (Figure-5).

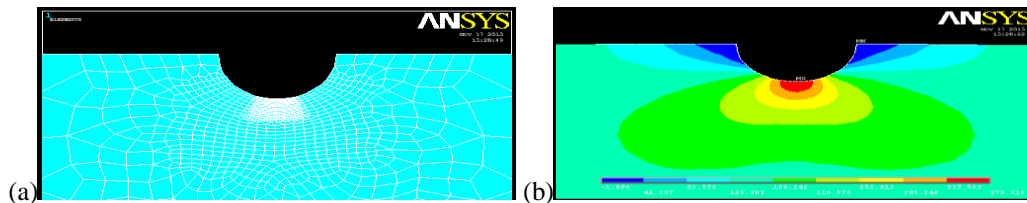


Figure . 6. :

(a) Meshed geometry;

(b): Results of calculating the distribution of the crack opening stress (σ_{yy}).

Solving the nonlinear problem will be carried out by an iterative algorithm that takes into account the plastic behavior of the material. In order to avoid any divergence problem, we limit the number of iterations at 1000.

The results in Figure-6 (b) show the maximum stress value observed in the vicinity of the notch root which is 379.41 MPa, resulting in a stress concentration factor of 2.53. Theoretically, the circular defect generates a Kt coefficient equal to 3. This difference is mainly due to the plasticity at the notch tip and the small thickness of the plate.

c. Elastoplastic thermal modeling of residual stresses

The state of residual stresses is multi-axial after welding, several studies have tried to model these stress numerically [9] by thermal elastic-plastic coupled models. Obtained results are disputable due to the nonlinearity of the physical phenomena involved during the welding process. It is noted that the majority of these models are based on the determination of the temperature field and its evolution over time as a first result (Figure-6). It is thereafter that the mechanical phenomena are modeled as a function of the evolution of the temperature obtained. This modeling requires perfect knowledge of the evolution of the mechanical parameters of the material depending on the temperature (Young's modulus, yield strength) and the evolution of thermal material parameters (conductivity, density, heat capacity ...). The data about these parameters allows conducting calculus of expansion and internal efforts by the finite elements during the cooling cycle to deduce the final state of stress and strain at the end of cycle.

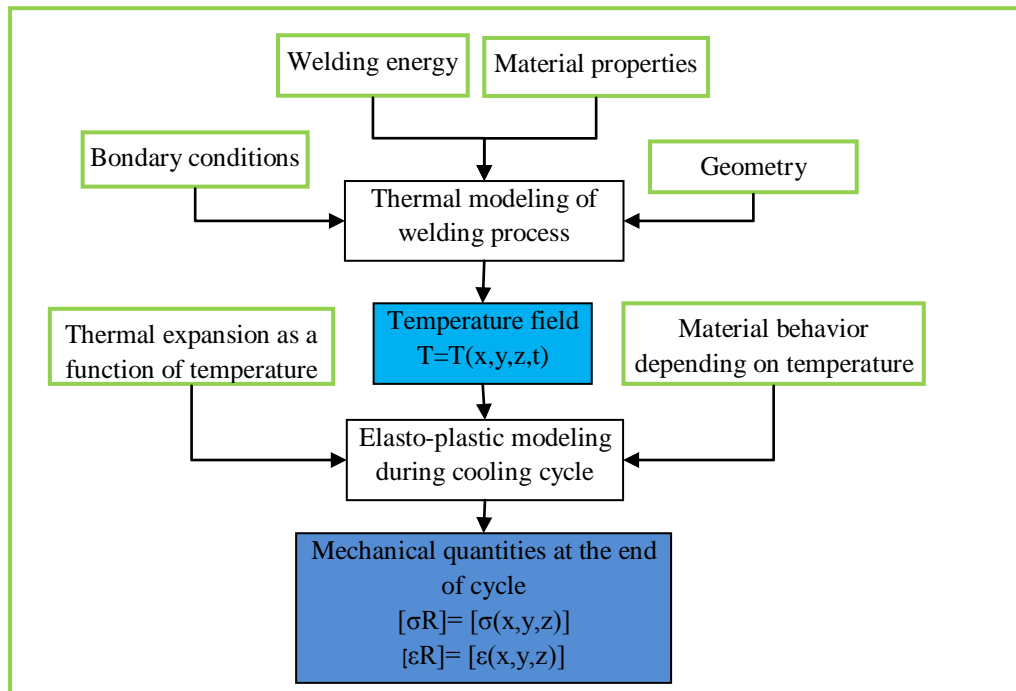


Figure .7. Main steps to modeling residual stress after welding process

Physical parameters to modeling residual stresses:

To illustrate the influence of residual stress on the weld strenght, the results of thermal elasto-plastic modeling performed on the same geometry studied [9] is adopted. This model takes into account the kinetics of the heat source movement in the welded part to predict the temperature distribution in time and space, and the influence of temperature on the various mechanical and thermal parameters material during the heating and cooling cycle (conductivity, heat capacity, density, Young's modulus).

Table 3: Modeling parameters

Operating parameters of the welding process	Thermal parameters of the material
Room Temperature: 20°C	Density (Kg/mm3) : $7,61 \cdot 10^{-6} < \rho(T) < 7,82 \cdot 10^{-6}$
Heat source speed : 3mm/s	Conductivity (J/mm s°C) : $5,31 \cdot 10^{-2} < \lambda(T) < 7,61 \cdot 10^{-2}$
Weld bead length : 10mm	Heat capacity (J/kg°C) : $408,3 < C_p(T) < 908,3$
Heat used : 4,5 J/mm3	Thermal expansion coefficient : $10^{-5} \text{ } ^\circ\text{C}^{-1}$
Convection coefficient (J/mm ² s) : $8,91 \cdot 10^{-6} < h < 9,1 \cdot 10^{-6}$	

d. Modeling results

The results of the distribution of the transverse residual stress are shown in (Figure 8, a). we choose to represent graphically the variation of the residual stress in a transverse distance X = 645mm where it reached its maximum value (fig 8, (b)).

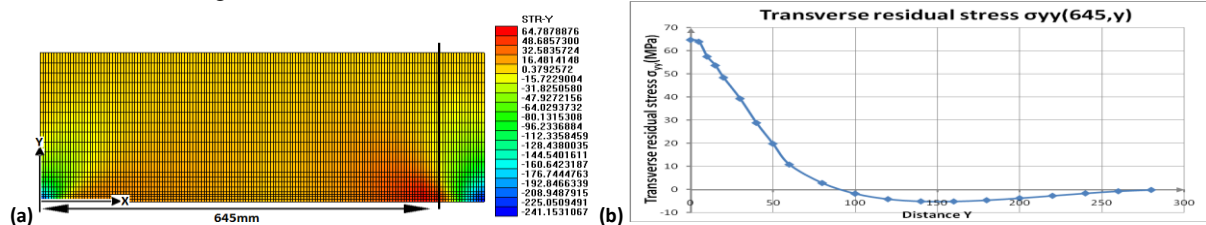


Figure 8. :

- (a) : Transverse residual stress distribution after welding $\sigma_{yy}(x,y)$
 (b) : Evolution of the transverse stress along the Y axis $\sigma_{yy}(645,y)$

The evolution of the transverse residual stress on the (Y) axis shows that it becomes compressive at a distance of 100 mm, it become null at the plate edge to satisfy the boundary conditions. To analyze the influence of welding defect, the maximum residual stress value will be used in this following paper.

Calculating the fatigue reduction factor by volumetric approach:

The first step is to determine the effective distance graphically by $\sigma_{yy}(z)$ curve plotted along the reverse direction of the (Z) axis. Determining (Z_{eff}) allow us to calculate (σ_{eff}) by numerical integration of the stress values of ($\sigma_{yy}(z)$) obtained by the finite element analysis.

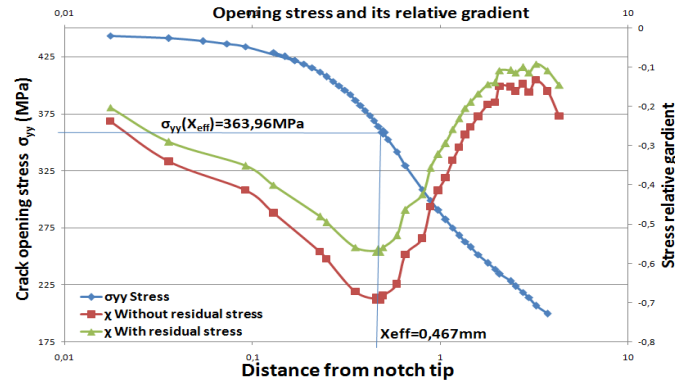


Figure. 9. Evolution of stress and its relative gradient on the vicinity of the notch

On the curve of the resulting $\sigma_{yy}(z)$ stress on figure-9, we find that this stress does not reach its asymptotic value of 150 MPa, this is due to the small thickness of the sheet compared to the defect radius. The curve of the two gradients plotted in the presence and absence of the residual stresses show the difference introduced by this stresses in calculus. If this stress is taken at a constant value it does not cause any variation in the gradient, on the other side the variation will be observed on the stress which is located in the $\chi(z)$ denominator. The difference between the two curves is observed mainly in the vicinity of the effective distance and is reduced in the area of maximum and minimum stress.

Fatigue reduction factor in the presence of residual stresses :

Using volumetric approach, reduction factor is calculated using the following expression [10].

$$K_f = \frac{1}{Z_{eff} \sigma_N} \int_0^{Z_{eff}} \sigma_{yy}(z) (1 - z\chi) dz \quad (13)$$

Using the numerical calculus of the integral based on the results obtained by the finite element calculation, we find the two values of the fatigue reduction factor Kf in the absence and presence of residual stresses. Without any residual stress we obtain 2.604 as a value of (Kf), while in case of the presence of these stresses we find that this factor is about 3.036, this increase is due to stability of the effective distance and raising of the residual stress values. Other methods of calculation can be used to estimate Kf, by the NEUBER method we find a value of 2.895, whereas the expression of PETERSON give a value of 2.824. The disparity between these results and the values of the volumetric method is mainly caused by theoretical foundation of PETERON and NEUBER models, developed for linear elastic behavior of the studied area.

IV. CONCLUSION

In the volume of welded assembly, the residual stresses are present due to heat cycle imposed by this process. The prediction of these stresses is complex mainly due to the nonlinear and coupled physical phenomena that are involved, which makes the results limited to specific materials and geometries. The impact of residual stress on the welds bead presenting defects on fatigue strength is a process studied following the reverse direction of the (Z) axis penetrating the plate. The determination of the distribution of residual stresses triaxial towards welded plates is a complex process, it is therefore necessary, as a first approach, to take the transverse residual stress as constant at least in the region of fatigue process very limited in a distance not more than 1mm in the majority of cases. The adoption of this assumption of stability give us the ability to apply the volumetric method by exploiting the stress field calculated statically which was added on the maximum transverse residual stress. Curves of the relative gradients calculated from the transverse stress allowed us to determine the size of the area of fatigue process was extended over a distance of 0.467 mm. Calculations that followed, demonstrate the detrimental effect of residual stresses revealed by a significant increase in Kf factor. It should be noted that we calculate the maximum value of Kf factor in this previous work, this is due to relaxation of the residual stresses observed in fatigue process which reduces significantly the intensity of these stress after the first cycles of load application [11].

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