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Effect of Mean Stress on Fatigue Crack Growth Behavior of Stainless Steel 304L

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Abstract**—**Stainless steel has been employed in many engineering applications ranging from pharmaceutical equipment to piping in the nuclear reactors and storage to chemical products. In this attempt, simulation of fatigue crack growth based on experimental results of austenitic stainless steel 304L was presented using AFGROW code when NASGRO mode laws adopted. Double through crack at hole specimen is used in this investigation under constant amplitude loading. Effect of mean stress is highlighted. Results show that fatigue crack growth rate (FCGR) and fatigue life were affected by maximum applied load and dimension of hole. An equivalent of Paris law for this material was estimated.

Keywords**—**Fatigue crack, stainless steel, mean stress, amplitude loading.

I. INTRODUCTION

MATERIALS of engineering components and structures are often subjected to cyclic loading with a positive mean stress. Fatigue crack propagation is usually analyzed by the application of LEFM (Linear Elastic Fracture Mechanics) concepts, described by the amplitude of stress intensity factor ΔK. Fatigue crack growth was affected by several parameters (metallurgical, environmental, geometrical, loading…etc).

For their high mechanical characteristic (capacity resistance, high strength, toughness, high corrosion resistance, hardness and impact resistance), the stainless steels remain not easily replaceable materials. Different grade of austenitic stainless steel used in the hostile environment are 301, 304, 304L, 316 …etc. These materials have been employed in many engineering applications (nuclear reactors, storage of chemical products…etc.). The material investigated in this work is 304L austenitic stainless. Many authors have been investigated the studied steel under different parameter effects [1-3] (thermal, fatigue, creep and fatigue, welding, Load history…etc. AISI 304L stainless steel weld was investigated experimentally by Singh et al [4]. It was shown that threshold stress intensity factor is about 10 MPa.Sqrt(m) and coefficients of Paris law (C, m) increase for GTAW welding process comparatively to the GMAW welding process.

The main loading parameter who affects the fatigue crack growth rate is stress ratio [5]. The effect of mean stress was characterised by this parameter. Kalnaus et al [6] have investigated new stainless steel named AL6XN on FCGR classified as a super-austenitic stainless steel with FCC austenitic structure. In this investigation, the results from the constant-amplitude experiments show a sensitivity of the crack growth rate to the R-ratio and the effect of amplitude loading was shown at lower stress intensity factor. In other work, the same authors [7] have recently conducted an influence of stress ratio, notch size in fatigue crack growth of 304L stainless steel on round compact tension specimen. The results show that the material displays sensitivity to the R-ratio. The early stage of crack growth from the notch is dependant mostly on the value of loading amplitude rather than on the notch geometry.

Recently, a low cycle fatigue effect on fracture behavior of 304 austenitic stainless steel was investigated by Duyi Ye et al [8]. The fatigue crack growth in low carbon austenitic stainless steels 304L and 316L were investigated by Yahiaoui and Petrequin [9]. Under the same solicitations (stress ratio, applied load), it has been shown that 316L steel present high resistance than 304L steel. The effect of specimen thickness on crack tip deformation and fatigue crack growth rate (FCGR) was investigated on stainless steel 304L [10]. The results shown that FCGR depend strongly of specimen thickness (an increasing in thickness, increase FCGR).

In this attempt, AFGROW code is used to simulate the crack growth from the double through crack at hole flat plate specimen made of the AISI 304L austenitic stainless steel. The mean stress characterized by stress ratio (R) and amplitude loading, and diameter of hole effects will be presented. The fatigue crack growth analysis is conducted by using NASGRO model.

II. FATIGUE CRACK GROWTH BEHAVIOR

A. The stainless steel specimen

The material used in this study is the stainless steel 304L (AFGROW database) obtained on rolled plates in L-T orientation. The basic mechanical properties for stainless steel 304L are in Table 1. Simulation of fatigue crack growth in mode I used finite plate with double through crack at hole when initial crack a_0 is shown on Fig. 1.

TABLE I
MECHANICAL PROPERTIES OF STAINLESS STEEL 304L

$\sigma_{0.2}$ (MPa)	K_{IC} ($MPa.m^{0.5}$)	E (GPa)	ν
275.79	219.77	206.84	0.33

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The stress intensity factor for the studied specimen implemented in AFGROW code depends on several parameters and is written bellow:

$$\Delta K = \sigma\sqrt{\pi . a} . \beta\left(\frac{a}{r}\right) \quad (1)$$

where β is the geometry correction factor, proposed by Newman [11], is expressed below (Eq. 2):

$$\beta\left(\frac{a}{r}\right) = 1 - 0.15\lambda + 3.46\lambda^2 - 4.47\lambda^3 + 3.52\lambda^4 \quad (2)$$

where: $\lambda = 1/\left(1 + (a/r)\right)$

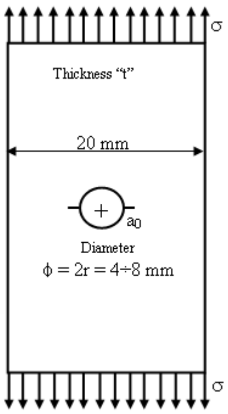

Fig. 1 Finite plate specimen (double through crack at hole)

B. Fatigue crack growth model

AFGROW code developed by NASA [12] is used for simulation of fatigue crack growth. The interest model is NASGRO model when totality of fatigue crack growth curves is considered. NASGRO model are expressed by Eq. 3:

$$\frac{da}{dN} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{\left(1 - \frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1 - \frac{K_{max}}{K_{crit}}\right)^q} \quad (3)$$

The parameters C, n, p, q are empirically derived from experimental results and f present the contribution of crack closure. ΔK_{th} present the crack propagation threshold value of the stress–intensity factor range. For constant amplitude loading, the function f determined by Newman [12]. The parameters of NASGRO model for the studied materials is presented in Table 2.

TABLE II
PARAMETERS OF CRACK GROWTH MODEL

C	n	p	q
1.1486×10^{-11}	3	0.25	0.25

III. RESULTS AND DISCUSSION

A. Mean stress effect

Plate specimen in L-T orientation was subjected to a constant loading with different mean stress characterised by stress ratio. The K_{max} failure criteria were adopted for the limit of crack growth. Fig. 2 showed the effect of mean stress (R-ratio) on fatigue crack growth rate of 304L stainless steel. An important effect of mean stress has been observed for this material at low and high stress intensity factor range ΔK. A general increase in da/dN with mean stress (σ_m) for a given ΔK has been observed. The same effects have been observed in others works [13]. In Paris region, the same slope of FCGR is shown. Variation of the mean stress depends more than the maximum stress or minimum stress for the same stress ratio.

Fig. 3 shows the evolution of FCGR of stainless steel 304L for two maximum amplitude loading with the same stress ratio. An increasing of maximum stress increase mean stress, this is increase the stress intensity factor range (6.7 to 12.50 $MPa.m^{1/2}$) and increase the FCGR.

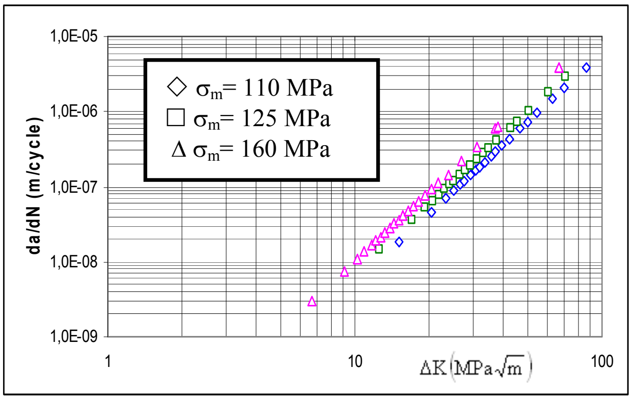

Fig. 2 Effect of mean stress on FCGR (R-ratio effect)

Fatigue crack growth rate of 304L stainless steel is presented on Fig. 4 and compared to 316L [14]. No high difference of resistance in FCGR is shown for both materials contrarily to the experimental work investigated by Yahiaoui and Petrequin [9]. Obtained results correlated by Paris law is also shown given by Eq. 4.

$$\frac{da}{dN} = 6\times10^{-12}\Delta K^{3.067} \quad (4)$$

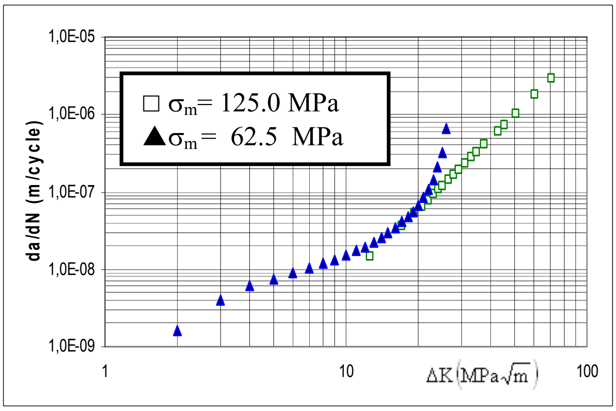

Fig. 3 Effect of mean stress on FCGR (amplitude loading effect)

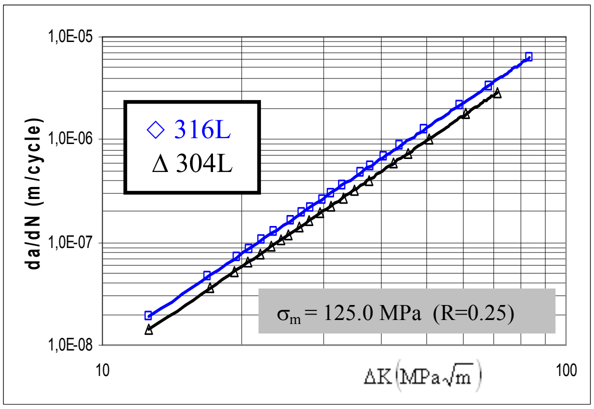

Fig. 4 Comparison in FCGR of two stainless steel (304L/316L)

B. Effect of hole diameter

The variation of hole diameter affect considerably the fatigue life and FCGR. The effect of increasing of hole diameter on fatigue life is shown on Fig. 5. The difference between hole with 4 mm and 8 mm is 3.5 times. The fatigue crack growth resistance is decreased in initial crack, characterized by increasing of stress intensity factor and FCGR (Fig. 6.).

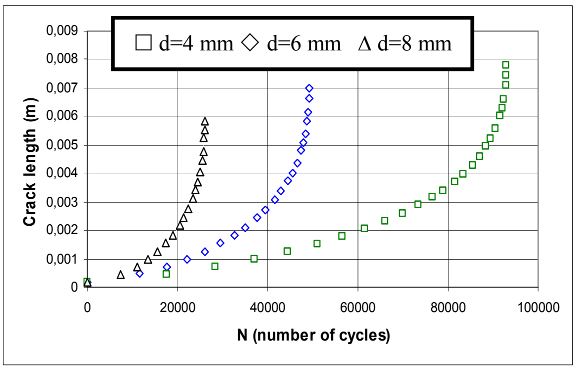

Fig. 5 Evolution of fatigue life of 304L stainless steel (R=0.25)

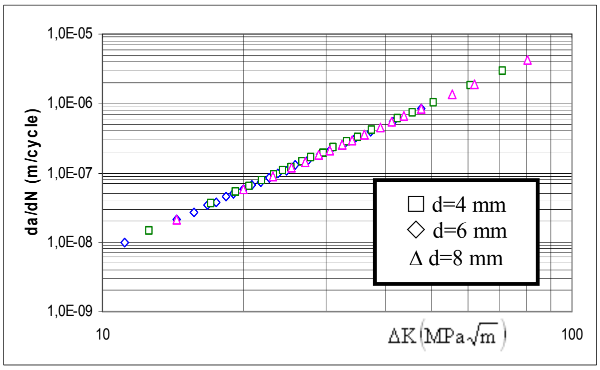

Fig. 6 Evolution of FCGR under diameter hole effect

IV. Conclusion

Fatigue crack growth behavior of 304L stainless on the double through crack at hole plate specimen is investigated in this work. The main conclusions are cited below:

- Evolutions of fatigue crack growth rate are affected by mean stress in variation of stress ratio (R) and maximum amplitude loading.
- An increasing of mean stress (R-ratio) increase the fatigue crack growth rates.
- An increasing of hole dimension, decrease fatigue life.
- No high difference resistance of the studied material comparatively to the 316L stainless steel.

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