Fatigue crack growth of double fillet weld in pressure vessels steels: effects of geometrical parameters of crack

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Résumé :

Un simple défaut existant après l'opération de soudage peut générer une rupture catastrophique. Dans cet article, on étudie la propagation des fissures de fatigue d'une double soudure d'angle avec l'existence d'une fissure semi elliptical. Deux types d'aciers pour cuves sous pression sont étudiés en plus de l'acier inoxydable 316L. Pour l'analyse de la propagation des fissures on applique la mécanique linéaire de la rupture et les paramètres de fissuration par fatigue des matériaux afin de déterminer la vitesse de propagation et comment le défaut se propage. L'effet sur la durée de vie en fatigue des paramètres géométriques de la fissure (rapport a/c), l'angle d'inclinaison du cordon de soudure et le niveau de chargement cyclique sont étudiés. Afin de prédire le comportement en fatigue de la structure soudée, un chargement à amplitude constante est appliqué sous l'influence du rapport de charge sur la durée de vie en fatigue. Une étude comparative de la propagation des fissures de fatigue des aciers cités est détaillée afin de montrer l'effet des sus indiqués.

MOTS CLÉS : Fatigue, Soudage, fissure semi elliptique, Aciers appareils sous pression, rapport de charge

Abstract:

A simple existing defect after welding can generate a catastrophic fracture. In this paper fatigue crack growth of a double fillet weld with the existence of a semi-elliptical crack is investigated. Two types of pressure vessels steels are studied additionally to stainless steel 316L. Crack growth analysis uses linear elastic fracture mechanics and related crack growth material properties to determine how fast a crack or crack-like defect will grow. The effect on the fatigue life of the geometrical parameters of the crack (a/c ratio), the angle of inclination of the weld bead and the level of loading are studied. In order to predict the fatigue behavior of the welded structure, a constant amplitude loading is applied where the influence of the stress ratio over the fatigue life is presented. A comparative study of fatigue crack growth of the cited steels is detailed in order to show the effect of several parameters.

KEYWORDS: Fatigue, weld, semi-elliptical crack, pressure vessels steels, stress ratio

1. Introduction

Pressure vessel and boiler steel plate is widely used in the fabrication of boilers and pressure vessel, such as petroleum, chemical, gas industry and power plants. Steel A542 is an alloy of Iron and Chromium-Molybdenum-Vanadium and approximately 0.15% Carbon, quenched and tempered. It is especially used to fabric high temperature pressure vessels [1]. Also, Steel A517 is a steel alloy of with the chemical composition Carbon (between 0.08-0.22), Nickel 0.60%, Silicon (0.65%), Chromium (1%) and other alloys elements such as Copper and Vanadium [2]. This alloy is intended for the manufacture of high pressure tanks. Stainless steels are primarily of steel, i.e. metal alloys Fe–C. The addition of chromium, the essential element to the corrosion of steel, led to the development of various grades of steel, and then stainless qualified. For the phenomenon of passivity of a steel can establish and sustain, it is necessary that the alloy has a minimum chromium content in the range of 10–11%, chromium is in solution [3]. Beyond this concentration, steel form spontaneously in the surface layer and protective continues chromite Cr2O3. Austenitic stainless steels at ordinary temperature retain CFC austenitic.

The fatigue life of a weld is usually less than of the metal which it joins. This fact can be attributed to several types of discontinuities, internal flaws, or metallurgical discontinuities which serve as stress concentrators and accelerate fatigue damage in their locality [2]. The fatigue crack propagation portion of the fatigue life is predicted in specified loading history, material and environment by empirical law [4-6].

In the investigation of Al-Mukhtar et al [7], the fatigue life of welded joint was calculated based on numerical integration of simple Paris law and a reliable solution of the stress intensity factor. In general, notches have greater effect on fatigue resistance than any other parameter, and a weldment generally contains notches. Notches include: changes in section due to reinforcement or weld geometry, surfaces ripples, undercuts and luck of penetration. In full penetration transverse butt welds with reinforcement intact, fatigue cracks are initiated at the weld toe where geometric stress raiser exists [8]. Butt welds tested in fatigue with their reinforcement intact exhibit less fatigue resistance than plain plate or butt welds with their reinforcement removed due to the notch associated with the toe of the weld [9]. The effect of butt weld geometry parameters (weld toe, flank angle, plate thickness, initial crack geometry) on the fatigue crack propagation life have been studied [10] by using Linear Elastic Fracture Mechanics (LEFM), Finite Element Analysis (FEA) and superposition approaches.

Fatigue loading at constant amplitude loading is characterized by mean stress, stress ratio, range of amplitude loading. Mean stress is known to have a strong effect on fatigue life. As cracks remain opened in the presence of tensile mean stress, the effect is to shorten life [11]. The resulting effect of an increase of R on da/dN has been investigated on some materials and especially in pressure vessels steel [12, 13]. In study conducted by Rickerby and Fenici [14], fatigue crack growth effect of mean stress (mean applied loading) was investigated on parent stainless steel. An increase in mean stress increases the fatigue crack growth rate. Additionally thickness and stress ratio effects on fatigue crack were investigated. The effect of stress ratio “R” on the fatigue crack propagation behavior of stainless steel gas metal arc welds was evaluated by Kusko et al. [15]. For the stainless steel gas metal arc welds, an R-ratio of 0.55 has been shown to overcome crack closure over all growth rate regimes. This study was aimed to investigate the effect of the geometrical parameters of double fillet on fatigue crack growth of pressure vessel steel and stainless steel.

2. Evaluation of fatigue life in double fillet weld joint

Semi-elliptical surface cracks occur frequently at the weld toes of welded joints [16]. Fatigue crack growth rate is usually analyzed in terms of fracture mechanics by using relations involving stress intensity factor. The fatigue process under constant amplitude loading can be described by the following equation:

$$\frac{da}{dN} = f\left(\text{a}K, R\right) \tag{1}$$

where ΔK is stress intensity factor and R is stress ratio.

In order to analyze the fatigue behaviour in welded joints using fracture mechanics techniques, it is necessary to calculate the value of the stress intensity factor of the fatigue crack. It is known that the stress intensity factor (K) for crack opening mode (mode I) can be expressed in the following form:

$$K = \quad \pm.\sqrt{\text{®}.a} \tag{2}$$

A correctional factor Mk was introduced for considering the effect of welding geometry for the cracks which propagate in the region of stress concentrations produced by the geometry of welded joints, i.e. cracks at weld toes, a further correction factor (Mk) is introduced and known as geometry magnification factor [17]. Then Eq. (3) can be written as follows:

$$K = \ _0.M_k \pm .\sqrt{\text{®}.a} \qquad (3)$$

The geometry of a double fillet weld is shown in Fig. 2 and mechanical properties of studied materials are given in table 1. To predict the effect of several parameters on fatigue crack growth, a fatigue calculator code is used. Crack growth analysis requires a crack growth curve for the material. The linear portion of the curve represents stable crack growth and is characterized by an intercept (C) and slope (m).

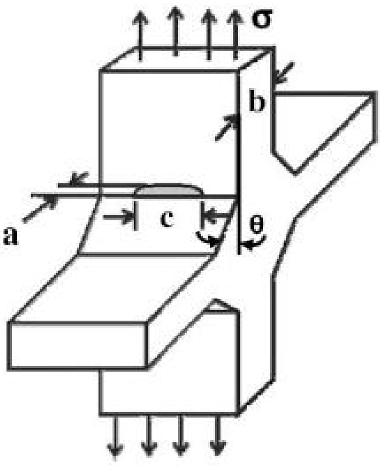

Figure 1. Semi-elliptical crack in double fillet weld

Table 1. Mechanical properties and propagation parameters

Materials	E (MPa)	C (m/cycle)	ΔK_{TH} ($MPa\sqrt{m}$)	m
A316	190000	4.26E-13	5.15	3.6
A517	207000	5.28E-12	4	3.39
A542	207000	8.02E-12	7.3	3

3. Results & Discussion

In this investigation tensile cyclic loads with maximum applied stress ("σ_{max}=180 MPa" are applied on double fillet weld specimen. Figures 2, 3 and 4 shown the evolution of crack length “a” in function of numbers of cycles “N” for applied stress ratio R=0.2 under variation of ratio “a/c” and angle “θ” characterizing the geometrical parameters of crack and weld. The semi-elliptic crack to propagate from the initial size a_0=1mm to the final size a_f=10mm.

Figure 2 presents the number of cycles of crack growth in variation of geometrical ratio “a/c” where this ratio varies form 0.1 to 0.3 and θ=30°. The fatigue lives are respectively equal to 1.55×10^5 cycles, 2.7×10^5 cycles and 4.36×10^5 cycles. The increase in ratio of fatigue life is 1.75 and 1.60 respectively for a/c=0.2 and 0.3 comparatively to the fatigue life for a/c=0.1. For θ=45°, the ratios in fatigue are 1.16 and 1.8 times. For θ= 60°, the same tendency is observed (figures 3 and 4). From these results, the fatigue lives are proportional to the ratio “a/c” and the increasing the angle “θ” affect negatively the fatigue life.

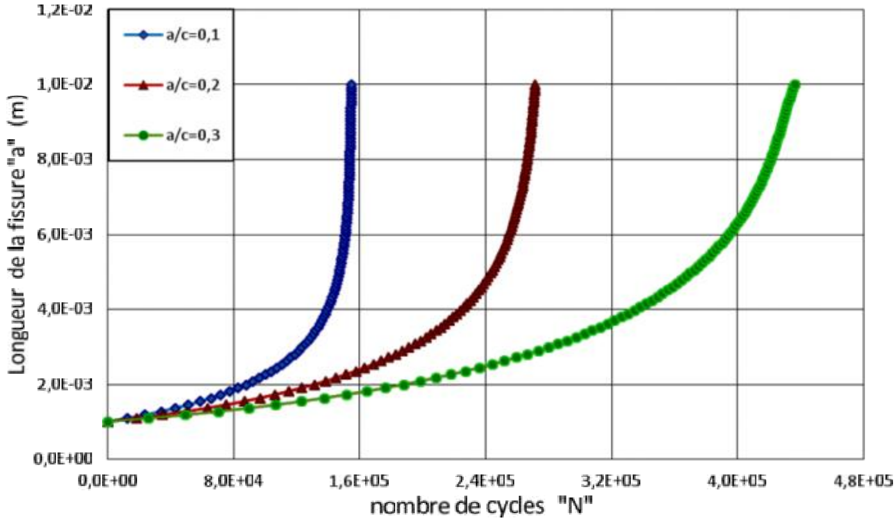

Figure 2. Effect of ratio “a/c” on fatigue life of A542 pressure vessel steel for ¯=30°

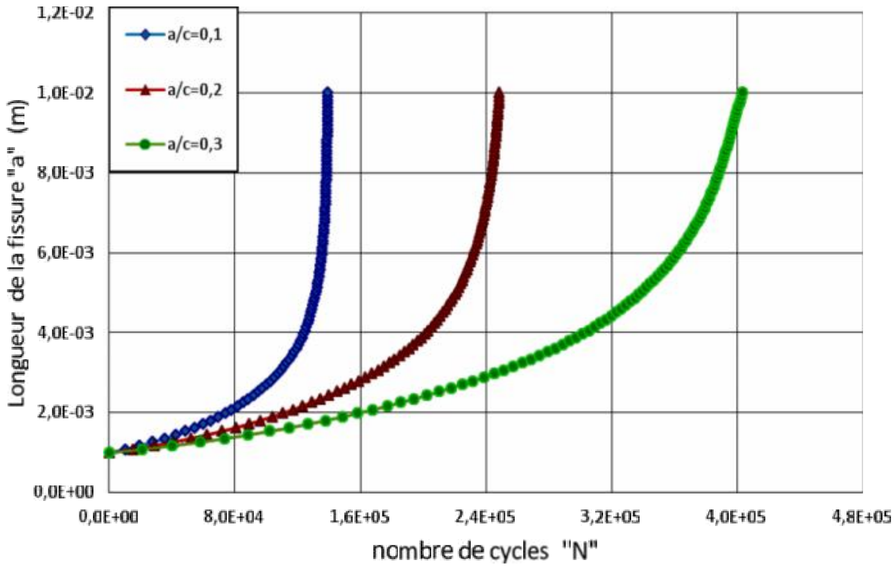

Figure 3. Effect of ratio “a/c” on fatigue life of A542 pressure vessel steel for ¯=45°

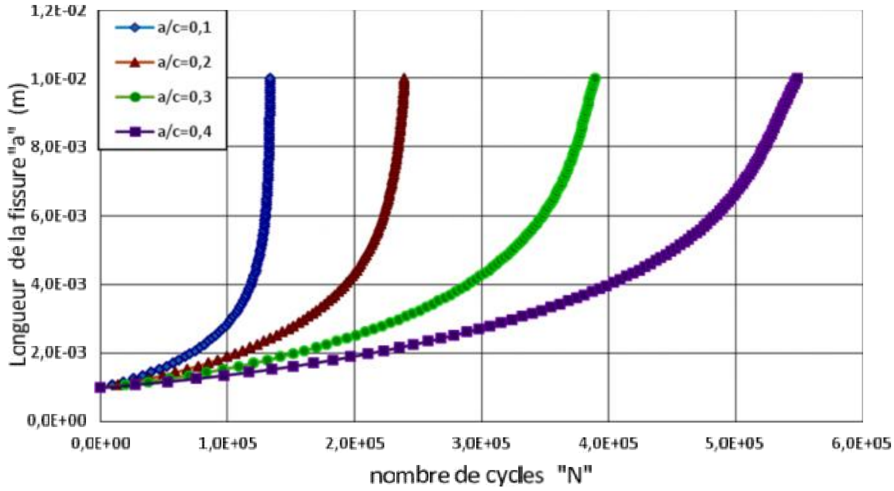

Figure 4. Effect of ratio “a/c” on fatigue life of A542 pressure vessel steel for ¯=60°

Figures 5 and 6 present the effect of angle of weld "θ" on fatigue life of welded joint for specified geometrical ratio (a/c=0.2, 0.3). For a/c=0.2, it was shown an increasing in fatigue life under reduction of angle of weld "θ". The numbers of cycles when the crack reach the final crack are respectively N $=2.39\times10^{5}$ cycles, N $=2.48\times10^{5}$ cycles et N $=2.71\times10^{5}$ cycles for "θ=30°, 45° and 60°". Also, for a/c=0.3 (figure 6), the fatigue lives N =3.89×105 cycles, N $=4.03\times10^{5}$ cycles and N $=4.36\times10^{5}$ for the angles.

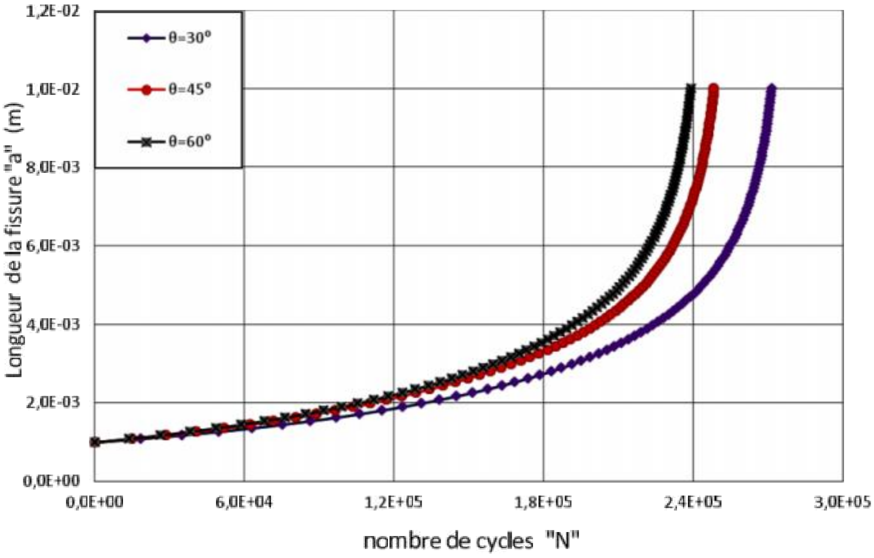

Figure 5. Effect of weld angle "¯" on fatigue life of A542 pressure vessel steel for ratio "a/c=0.2"

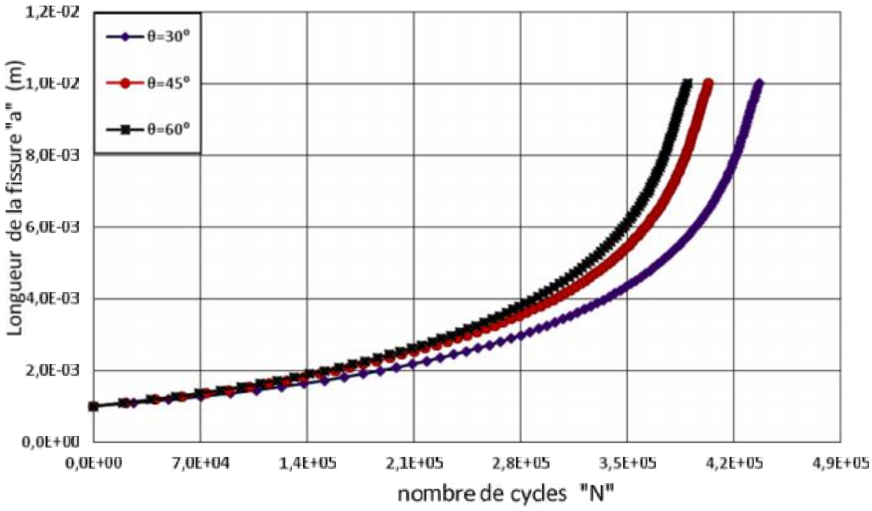

Figure 6. Effect of weld angle "¯" on fatigue life of A542 pressure vessel steel for ratio "a/c=0.3"

The comparison in evolution of fatigue life of the three materials (A542, A517 and 316L) is made for fixed stress ratio "R=0.2" and geometrical ratio "a/c=0.2"and variation of angle of weld (θ=30°, 45° and 60°) (figures 7, 8 and 9). It is noticed that that the increase in weld angle "θ", affect the fatigue lives by decreasing them.

At weld angle θ=30° and 45°, the stainless steel A316L requires high numbers of cycles to reach specified final crack (about 106 cycles). Contrarily, pressure vessels steel A542 with the same final crack, the numbers of cycles are respectively 2.7×10^{5} cycles et 2.4 $\times10^{5}$ cycles all weld angle and for A517, the fatigue lives close the values $1{,}5\times10^{5}$ cycles et $1{,}4\text{x}10^{5}$ cycles.

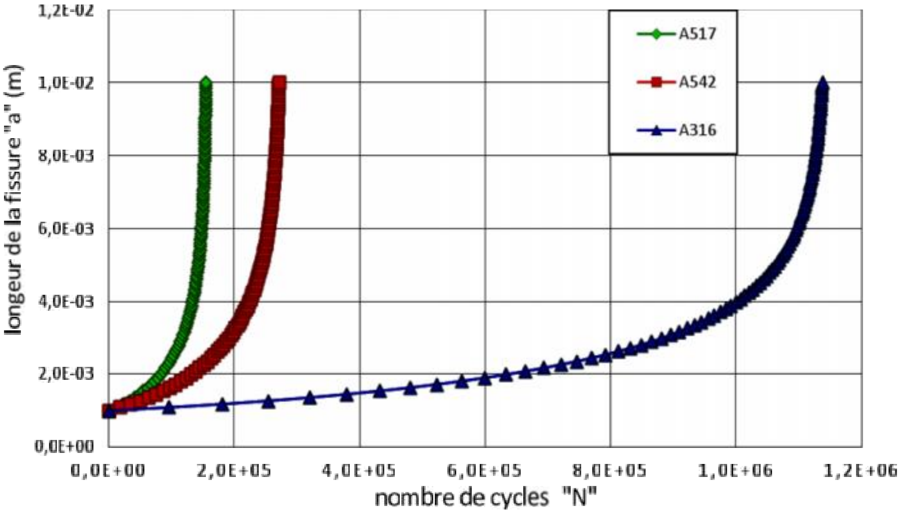

Figure 7. Evolution of crack length for a/c=0,2 et θ=30°

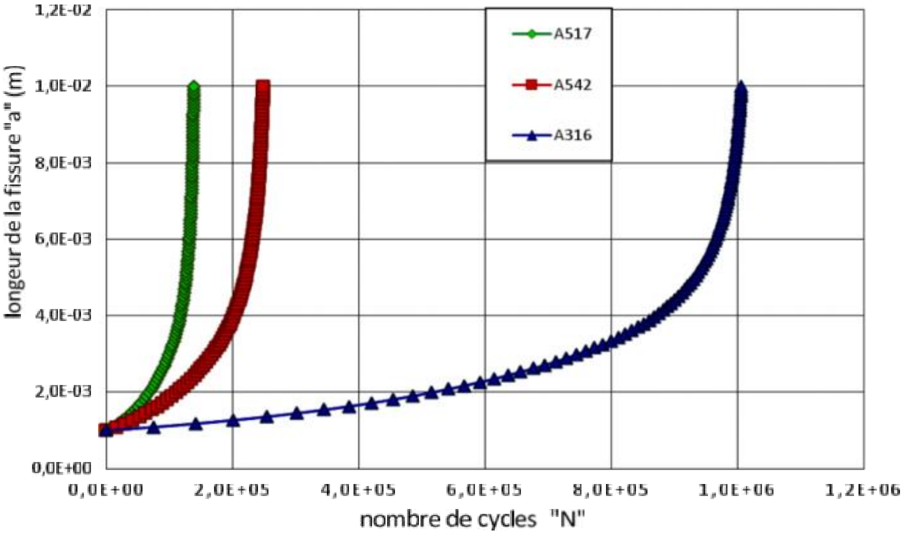

Figure 8. Evolution of crack length for a/c=0,2 et θ=45°

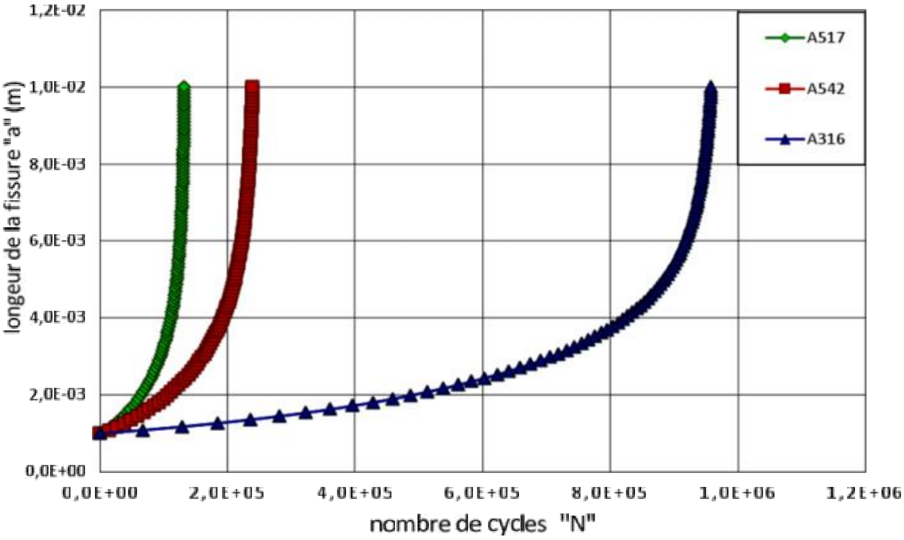

Figure 9. Evolution of crack length for a/c=0,2 et θ=60°

4. Conclusion

The paper presented the fatigue crack growth of a double fillet weld with exiting of semi-elliptical crack. Pressure vessels steels (A542 and A517) and stainless steel (316L) are studied. From the obtained results, conclusions can be drawn:

- The total fatigue life is affect by geometrical parameters (a/c) of semi-elliptical crack. The increasing of this ratio, increase the fatigue life.
- The increasing in orientation of angle of weld joint presents harmful effect on fatigue crack growth.
- The stainless steel presents a high fatigue resistance to pressure vessels steel.

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