Recueil De Mécanique
El Wancharissi University
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Research Paper DOI : 10.5281/zenodo.5918512 Open access

Effect of thermo-mechanical residual stresses on fatigue crack propagation

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ARTICLE INFO

Article history :

Received 05 Jully 21

Accepted 08 September 21

Keywords:

Thermomechanical residual stresses; numerical analysis; Fatigue crack propagation; Crack tip, Prediction of fatigue life.

ABSTRACT

In this paper we present the influence of residual stresses on the behavior of fatigue cracks under thermo-mechanical loading. Propagation modeling is performed using the global stress intensity factor approach, which describes the simultaneous influence of residual stress field and applied stress on crack propagation. The residual stresses are generated by a thermal loading. These stresses are the result of incompatibilities of deformation related to the heterogeneity of the plastic deformation. They will be superimposed on the loading of fatigue and thus modify the average stress. These residual stresses relax under the effect of fatigue loading, by keeping the crack closed or open, according to the stress cycle.

1 Introduction

The durability of components and structures subject to cyclic loading is a permanent concern in the transport sector. Maintenance services (aeronautics, hydraulics, road transport, etc.) often have to deal with the appearance of cracks that can start and propagate in the metallic elements of structures subjected to cyclic loading.

Increasing the life of mechanical parts is part of a process of sustainable development. To achieve this, slowing down or stopping the propagation of a fatigue crack can be obtained by reducing effective local stresses, reducing local stress concentrations, introducing residual compressive stresses , strengthening the cracked materials [1-4].

These actions constitute methods which lead to the reduction of the effective stresses at the bottom of a crack and consequently to the repair (arrest or notable slowdown of the crack) of the components cracked by fatigue. Indeed, the residual stresses on the propagation of the fatigue crack are of great importance and have been the subject of several research works [5-7]. It has long been established that the initiation phase of fatigue cracks is strongly influenced by the presence of residual stresses [8-12]. Compression stresses can delay or prevent the appearance of fatigue microcracks by

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acting as medium stresses counterbalancing the stresses applied [13-15]. High residual compressive stresses can also cause the propagation of a micro-crack to stop [16]. Residual tensile stresses, on the contrary, tend to favor the formation of micro-cracks [17].

Panda et al. [18] showed that the combined effect of the residual compressive stress and the hardening improves to the fatigue strength. Song et al. [19] studied the optimization of treatment conditions on the development of residual thermal stresses to minimize their effect on residual stresses. Many authors [20-21] have studied the distribution of residual stresses around the crack tip and have found that their effect on the propagation of fatigue cracks is relatively weak. The effects of residual stresses induced during welding (friction-stir welding of alloys), parallel and perpendicular on the growth of fatigue cracks, have been studied [22-26]. The influence of the residual stress field on the propagation of fatigue cracks in prestressing steel wires has also been studied by Toribio et al. [27]. The influence of the loading parameters such as the load ratio, and the overload rate, using the effect of residual stresses, on both crack propagation, propagation speed and fatigue life prediction, is investigated by Salmi et al. [28]. Also, Bahram et al. [29] have studied the influence of the load ratio and temperature on the crack propagation rate along cracks on the outer surface.

The aim of this paper is a numerical simulation of the effect of thermo-mechanical residual stresses on fatigue crack propagation and fatigue life prediction of structures, which allowed us to study their effect by the variation of two parameters, temperature and rate loading, using the AFGROW code [30].

2 Generation of residual stresses

The numerical approach to the generation of residual stresses was made by Kebir et al. [21].The distribution of the residual stresses along the direction of the propagation of cracks on compact tension specimens (CT) was carried out according to the standards of ASTM E647[31], using the finite element method, software Abaqus. The geometry and dimensions of the test specimen are given in figure 1.

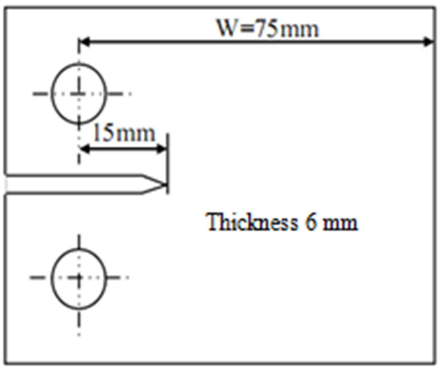

Fig. 1 – Compact tension (CT) Specimen test (ASTM E647).

The study is carried out on an aluminum alloy 2024 T351 whose mechanical properties vary as a function of temperature [32] and have been given in the table 1.

The loading rate is the report between the applied stress σ and the yield stress σ_Y and it is defined by:

$$\tau = \frac{\sigma}{\sigma_Y} \quad (1)$$

Four values of loading rate are used τ = 1.01, 1.05, 1.10 and 1.15. For each loading rate, the mechanical loadings are carried out proportional to each mechanical behavior at known temperatures and vary from 25 °C to 200 °C [32]. Knowing that, the elastic-plastic behavior is also introduced in software Abaqus [21]. The results obtained show that:

The residual stresses at the crack tip for each step in the CT specimen are compressive in nature with decreasing absolute values as a function of the length of the crack.

The residual stresses at the tip of the crack are compression stresses which evolve with the evolution of the crack. Each crack advance, we see that the stresses residuals go through a compression phase and then a tension phase away from the point of the crack these stresses tend towards zero, therefore there is relaxation of the stresses.

Table 1 - Mechanical and physical properties of Aluminum Alloy 2024-T3 as a function of temperature

Temperature (°C)	Young's modulus E (MPa)	Poisson Coefficient υ	Stress Yield σ_Y (MPa)	Ultimate Stress σ_U (MPa)	Expansion α (°C^{-1})
20	70000	0,30	356	480	0,230
100	65000	0,32	346	464	0,238
150	60000	0,33	338	410	0,242
200	47000	0,34	310	377	0,246

These residual stresses are introduced in the AFGROW code for each rate loading and the different values of the temperatures.

3 Residual stresses on fatigue crack growth

3.1 Nasgro Model

The fatigue test simulations are done using the AFGROW code, which is software for calculating lifetimes. The model used is Nasgro [30] which expresses the fatigue crack growth rate (FCGR) by the following relation:

$$\frac{da}{dN} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{max}}{K_c}\right)^q} \quad (2)$$

Where

C, n, p and q are constants, ΔK_{th} is the range stress intensity factor at threshold, K_c critical stress intensity factor, R is the load ratio is defined as the ratio of the minimum and maximum loads during the fatigue loading defined by the relation (3)

$$R = \frac{K_{min}}{K_{max}} \quad (3)$$

The range stress intensity factor is defined following:

$$\Delta K = K_{max} - K_{min} \quad (4)$$

Where: K_{max} is the maximal stress intensity factor and K_{min} is the minimal stress intensity factor.

$$f = \frac{K_{op}}{K_{max}} = \begin{cases} \max(R, A_0 + A_1R + A_2R^2 + A_3R^3) \\ A_0 + A_1R \qquad -2 \le R \le 0 \\ A_0 + 2A_1 \qquad R < -2 \end{cases} \quad (5)$$

Where; A_0,: A_1, A_2 and A_3 are coefficients such as:

$$A_0 = (0.825 - 0.34\alpha + 0.05\alpha^2)\left[\cos\left(\frac{\pi}{2}\frac{\sigma_{max}}{\sigma_0}\right)\right]^{\frac{1}{\alpha}}$$

$$A_1 = (0.415 - 0.071\alpha + 0.05\alpha^2)\frac{\sigma_{max}}{\sigma_0} \quad (6)$$

$$A_2 = 1 - A_0 - A_1 - A_3$$

$$A_3 = 2A_0 - A_1 - 1$$

Where: α is plane stress factor, $\frac{\sigma_{max}}{\sigma_0}$ is the ratio between nominal stress and maximal stress.

The intensity factor of the residual stresses is calculated by the method called "Gaussian integration method"[22][30] is given by the following relation:

$$K_I = \sum_{x=0}^{a} \sigma_x^* \, f(a,x)dx \quad (7)$$

With

$$f(a,x) = \frac{2}{\sqrt{\pi a}} \frac{1.3-0.05\left(\frac{x}{a}\right)-0.2\left(\frac{x}{a}\right)^2-0.3\left(\frac{x}{a}\right)^3+0.25\left(\frac{x}{a}\right)^4}{\sqrt{1-\left(\frac{x}{a}\right)^2}} \quad (8)$$

The mechanical and physical properties of the Aluminum alloy 2024-T3 are directly given in the AFGROW software. Using the specimen C (T), these residual stresses are introduced in this software for each rate loading and the different values of the temperatures. We choose a stress ratio R = 0.33 for all tests, because to find the prediction of the fatigue life in the polygocyclic domain, i.e. to ensure the fatigue life between (10^5 - 10^8) which makes it possible to verify the effect of the phenomena of residual stress in a clear manner.

3.2 Fatigue crack growth rate

Figures 2 to 5 show the evolution of the fatigue crack propagation $\frac{da}{dN}$ as a function of the stress intensity factor (ΔK); it is found for the same rate loading that the crack propagation decreases when the temperatures decrease. The residual stresses created affect the behavior of the fatigue crack growth in the material by adding the intensity factor of the residual stresses (K_{Res}) to the intensity factor of the applied stress (K_{app}), is expressed by the following relation:

$$K_{Total} = K_{app} + K_{Res} \quad (9)$$

This superposition method has been applied in previous studies [22],[33]. The residual stresses also modify the load ratio R of the applied stress. In the absence of residual stress, R and ΔK are defined by relations (3) and (4). The superposition of residual stress intensity factor (K_{Res}) should be applied to both at (K_{max}) and (K_{min}). Equations (3) and (4) become:

$$R = \frac{K_{min}+K_{Res}}{K_{max}+K_{Res}} \quad (10)$$

The range stress intensity factor is defined following:

$$\Delta K = (K_{max} + K_{Res}) - (K_{min} + K_{Res}) \quad (11)$$

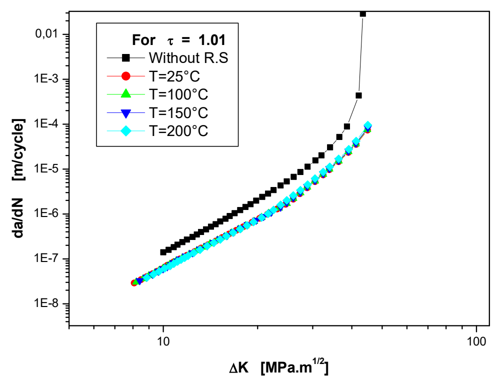

Fig. 2 – Evolution of fatigue crack growth versus ΔK, for the rate loading τ = 1.01

In general, the tensile residual stresses give positive K_{Res} values which increase the stress ratio applied and cause fatigue failure, while the compressive residual stresses give negative K_{Res} values which decrease the stress ratio applied, that is, the compressive residual stresses which boost the fatigue resistance and increase the service life of the components after heat treatment [34]. Alderliesten et al.[26] have suggested that when a full crack closure is achieved, the rigid crack closure condition should be removed and simple superposition was used in this case. The influence of residual stress (RS) field on fatigue crack propagation is considered the effective stress intensity factor range, which is calculated under the combined stress field of applied stress and residual stress [33][35-36]. The figure 14 and 15 show the evolution of fatigue crack growth rate $\frac{da}{dN}$ versus the stress intensity factor (ΔK); it is observed that the compressive residual stresses induce fatigue crack growth retardation for all different temperature [23-24].

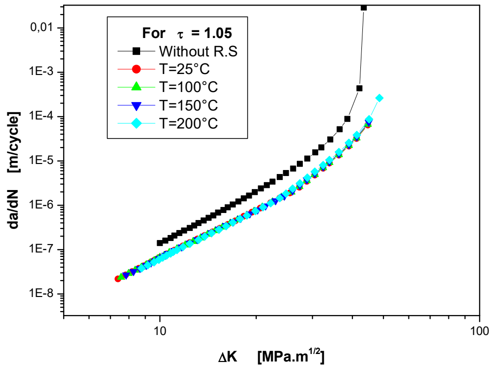

Fig. 3 – Evolution of fatigue crack growth versus ΔK, for the rate loading τ = 1.05

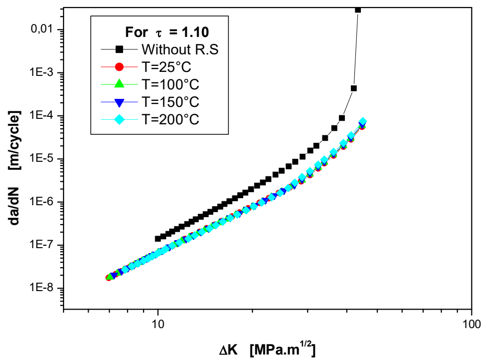

Fig. 4 – Evolution of fatigue crack growth versus ΔK, for the rate loading τ = 1.10

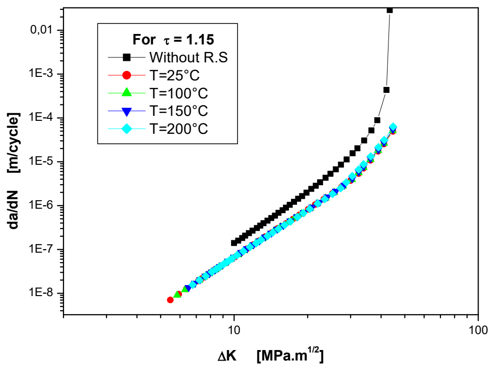

Fig. 5 – Evolution of fatigue crack growth versus ΔK, for the rate loading τ = 1.15

3.3 Fatigue life prediction

Figures 6 to 9 shows the evolution of the crack length versus of the number of cycle. We have noticed for the same rate loading, the temperatures decrease, increasing the fatigue life prediction , but at the same temperature, the fatigue lifetime increases when the rate loading increases, which validates the published results[35][37]. Also, a recent work [23] is study the effect of temperature on crack propagation is presented, giving the best lifetime prediction when the thermal is decreasing. Another, the distribution of residual stresses along the crack propagation is studied and their influence on the fatigue crack propagation is predicted [35-36].

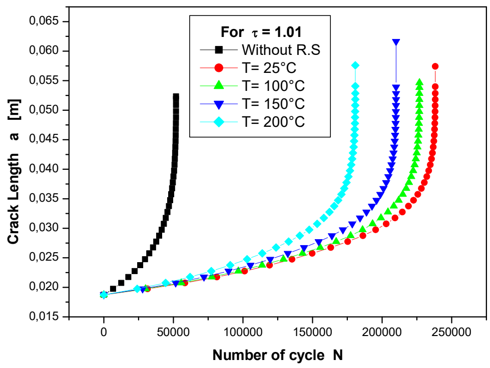

Fig. 6 – Evolution of crack length as function of the number of cycles N, for the rate loading τ = 1.01

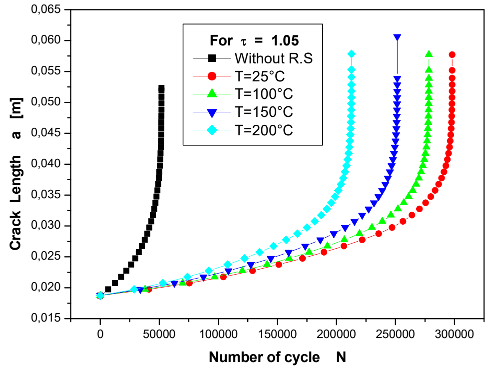

Fig. 7 – Evolution of crack length as function of the number of cycles N, for the rate loading τ = 1.05

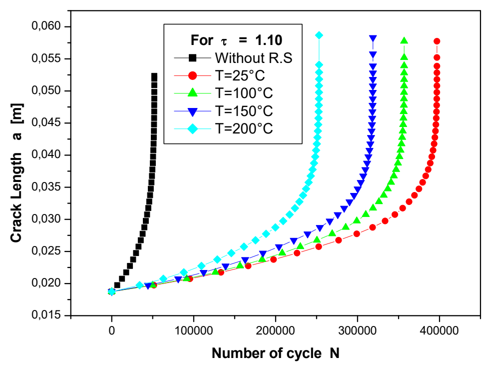

Fig. 8 – Evolution of crack length as function of the number of cycles N, for the rate loading τ = 1.10

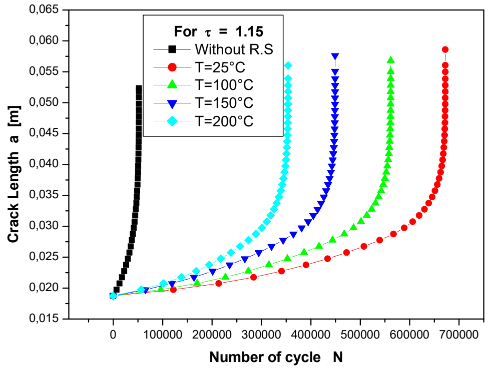

Fig. 9 – Evolution of crack length as function of the number of cycles N, for the rate loading τ = 1.15

The results of the fatigue life prediction for different parameters (Rate loading τ and temperature T) are resumed in table 2.

Table 2 – Fatigue life prediction with and without residual stresses for different parameters τ and T

	Life prediction N_f (cycles) with residual Stress				Life prediction N_f (cycles) Without residual Stress
Temperature T (°C)	**load rate τ=1.01**	**load rate τ=1.05**	**load rate τ=1.10**	**load rate τ=1.15**	51 944
25	238 254	298 001	396 929	672 198	
100	226 859	278 295	356 882	561 742	
150	210 090	251 520	318 764	449 077	
200	180 786	212 756	253 029	353 851	

In table 2, we note that for the same temperature, the long lifetimes are obtained for the highest rate loading (τ). For the same rate loading (τ), the lifetime increases when decreasing the temperature, this can be explained by the relaxation phenomenon of residual stresses when the temperatures increase causing a partial reversal of the field of residual stresses, change from the compression phase to a tension phase [21].

4 Conclusion

The main conclusions that were drawn from this study are:

- The residual stresses at crack tip are compressive stresses that evolve with the crack propagation.
- The crack propagation decreases as the rate loading increases and the temperature decreases. This phenomenon can be explained by the fact that an increase in the loading ratio and a decrease in temperature generate an increase in the intensity of the residual stresses at the bottom of the crack.
- For the same loading ratio loading as the life increases with decreasing temperatures.
- The influence of residual stress field on fatigue crack growth is considered the effective stress intensity factor range, which is calculated under the combined stress field of applied stress and residual stress, when residual stresses are very high the materials become poor in fatigue crack propagation.

- The residual stresses are limited the load capacity and safety of mechanical components during their exercise, and can find an effective answer only if they are known both quantitatively and qualitatively.
- As well as experimental evidence in the literature, the findings were shown to be in good agreement with each other.

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