Effect of Levels of Residual Stress at Notch on Fatigue Crack Growth

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Abstract In this paper, fatigue crack growth of finite plate with hole under constant amplitude loading through compressive residual stress at notch of aluminum alloys was investigated. Residual stress fields were generated by plastic deformation using finite element method. Based on fatigue crack growth rates (FCGRs) experimental data without residual stress, fatigue life and FCGR were predicted using AFGROW code. It was shown that the fatigue crack growth was affected by level of residual stress at notch for different level of plastic deformation. In this investigation, the presence of compressive residual stresses increase the total fatigue life and reduces the FCGRs. In addition stress ratio effect on fatigue behavior was studied.

Keywords Fatigue crack, Compressive residual stress, Al-alloy, notch, stress ratio

1. Introduction

Fatigue crack growth behavior is a significant issue in the establishment of inspection and maintenance procedures in variety industries such as aerospace, automotive, oil industries, rail...etc. This behavior is divided in three stages [1]: fatigue crack initiation, stable crack propagation and unstable crack propagation. Generally, mechanical components and structures contain geometrical discontinuities and notches. Stress concentration will be produced in theses discontinuities as a result of external force and depend of notch radius. The stresses are generally higher than the nominal values, and if precautions (good quality of machining of notch, induction of residual stress …etc.) are not taken into account, notches could be sites of crack initiation. Residual fatigue life of materials and structures depends on several parameters. In stable stage, fatigue life is linked strongly geometrical, loading parameters and residual stress. However, the stresses resulting from applied service loading are not the only stresses of significance for fatigue. Many components also contain residual stresses that were established prior to placing the component into service and which remain in place during the service life. These residual stresses are static load and influence the mean or maximum value of the load in each fatigue cycle. The residual stresses present diverse origin and several shapes [2-11] namely shot-penning, expansion of hole, overloads, underload, pre-strain or pre-deformation, welding, machining process… The stress field is beneficial if the stress is in compressive state [12, 15]. Contrary to this, the fatigue crack is accelerated [16]. Pre-strain is a process when preload induced plastic deformation, induced intentionally or not and create a residual stress field. The level and nature of these residual stresses depend on the amplitude and direction of applied load.
In the investigation of Kamel et al. [17] effects of tensile and compressive residual stress in fracture mechanics specimens by the application of a mechanical pre-load were studied using ‘C’ shape specimen. Finite element analysis is performed to simulate the pre-loading and the subsequent fracture loading of the cracked specimen. Recently, effect of residual stress on the fatigue behavior

of 2024 Al-alloy was studied experimentally and numerically using FEM by Al-Khazraji et al. [18]. Effect of plastic predeformation by bending to create deep residual compressive stresses on the fatigue strength of steel specimens and compressor blades was studied by Ezhov and Sidyachenko [19]. It was found that plastic predeformation increases the fatigue strength by about 20%. In other work, effect of residual stress induced by plastic predeformation was investigated by Mokhdani [20] on API 5L pipeline steel and Benachour [21] and Jones [22] on 2024 T351 Al-alloy using Four bent specimen. It was found that the fatigue life was influenced by the plastic preload. An increasing in fatigue life was shown by increasing of the level of plastic preload. The fatigue crack growth rates at low stress intensity factor were decreased by the presence of compressive residual stress. In study conducted by Jones and Dunn [23], fatigue crack growth from a hole with residual stress introduced by tensile preload was predicted using linear elastic fracture mechanics and the principle of superposition. O'Dowd et al. [24] introduced residual stresses in compact tension (CT) specimen by mechanical compression. The level of the compressive load was determined by finite element method (FEM). The compressive residual stresses present a beneficial effect on fatigue lifetime. Additionally fatigue life and fatigue crack growth rate (FCGR) were affected by stress ratio. Many researchers [25-28] have studied effect of this parameter on some Al-alloy with and without residual stress.

The main aims of the present investigation is to studied effect of residual stress on fatigue life and fatigue crack growth around hole, determined by plastic preload in tension of samples using finite element method.

2. Finite element model and analysis procedure

2.1. Modeling

The FE model used in simulation of plastic preload (PP) was a plate assumed to be made from Al-alloy 2024 T351 and 6061 T6. The mechanical properties of the both materials are shown in Table 1. In order to analyze the respect of elasto-plastic behavior, a true stress–true strain curve as shown in Figure 1 was used as an input property of FE analysis. As shown in Figure. 2, the dimensions of the plate containing Ø 6 diameter holes and thickness (t) = 4 mm. I have varied the level of applied preload characterized by non dimensional ratio σ_p/σ_y, where σ_p is applied preload and σ_y is yield stress for specified material, in order to investigate the level of the residual stress variation on fatigue crack growth behavior. The finite element mesh is shown in Figure 3. Only four quart of the entire plate has been modeled considering of the symmetry. More finite elements than those in other regions are put closer to the boundary of holes. Since we are interested of the residual stress variation according to the X axis from hole edge to free surface, two-dimensional analysis has been carried out with uniform distributed plastic preload σ_p. The program used in the FE analysis was ANSYS, Ver. 11. The mesh element type was "PLANE183".

Table 1. Mechanical properties for Al-alloys

Al-alloys	E (GPa)	σy (MPa)	UTS (MPa)	ν
2024 T351 [44]	74.08	363	477	0.33
6061 T6 [45]	69.04	252	360	

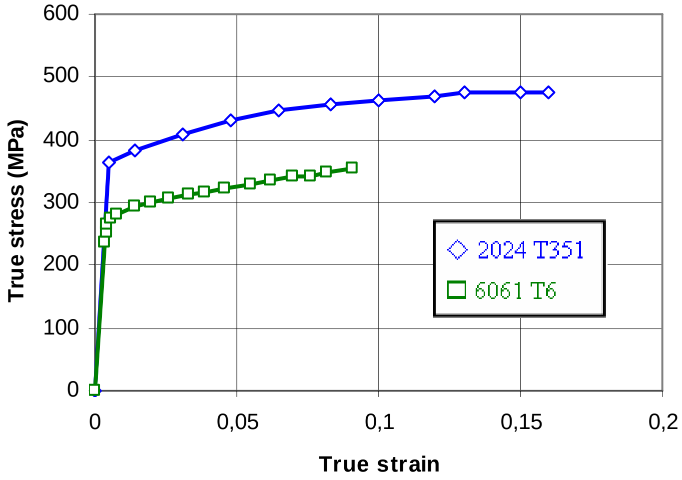

Figure 1. True stress–true strain curves of Al-alloy 6061-T6 and 2024 T351

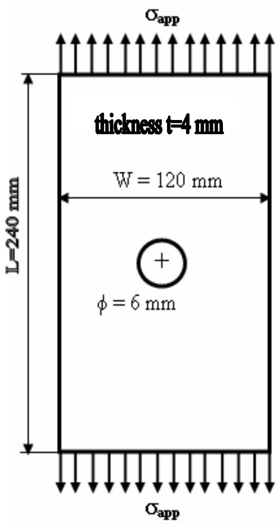

Figure 2. Analysis model

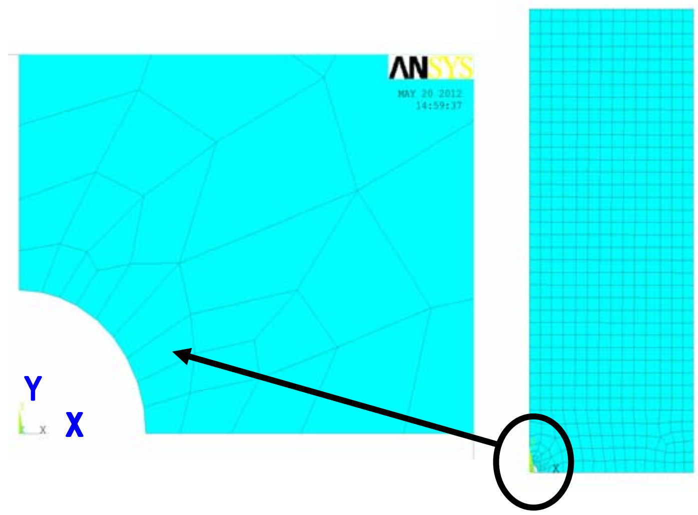

Figure 3. Quarter of finite element mesh with central hole

To generate a residual stress field, the applied load must exceed the elastic limit is to say that the force generated during the loading phase of plastic deformation where the isotropic plasticity model of Von Mises was used to account of the plasticity of material. The applied loading and unloading sequence (i.e. 2024 T351 Al-alloy) to generate residual stress by preload is shown in figure 4. The levels of preload is characterized by ratio σ_p/σ_y for both materials are shown in Table 2.

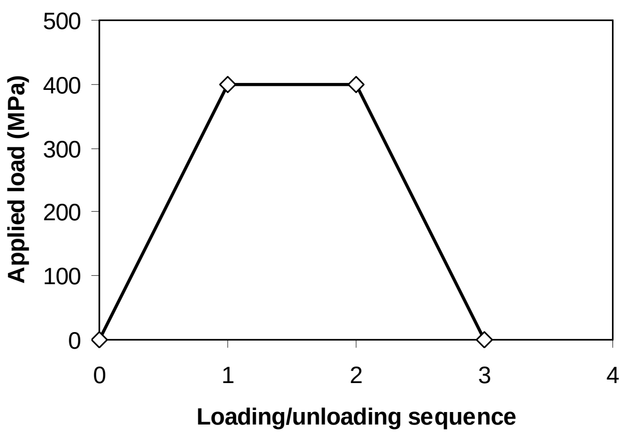

Figure 5. Loading sequence to generate residual stress

Table 2. Levels of preload for both materials

Al-Alloy	2024 T351	6061 T6
σp/σy	1.047	1.19
	1.102	1.23
	1.212	1.39
	1.350	

2.2. Generated residual stress

Under levels shown in Table 2, respective residual stress fields were generated. Figures 6 and 7 shown residual stress distribution around hole σ_{yy} for different applied preload for 2024 T351 and 6061 T6 Al-alloy respectively for specified levels. Interesting distributions of these residual stresses are along X-axis. X-axis is a planned path for crack propagation in mode I. Figure 8 shows variation of residual stress distribution σ_{yy} along X-axis for 2024 Al-alloy for different preload levels. It shows an increasing of compressive residual stress with increasing of preload levels at hole. was shown

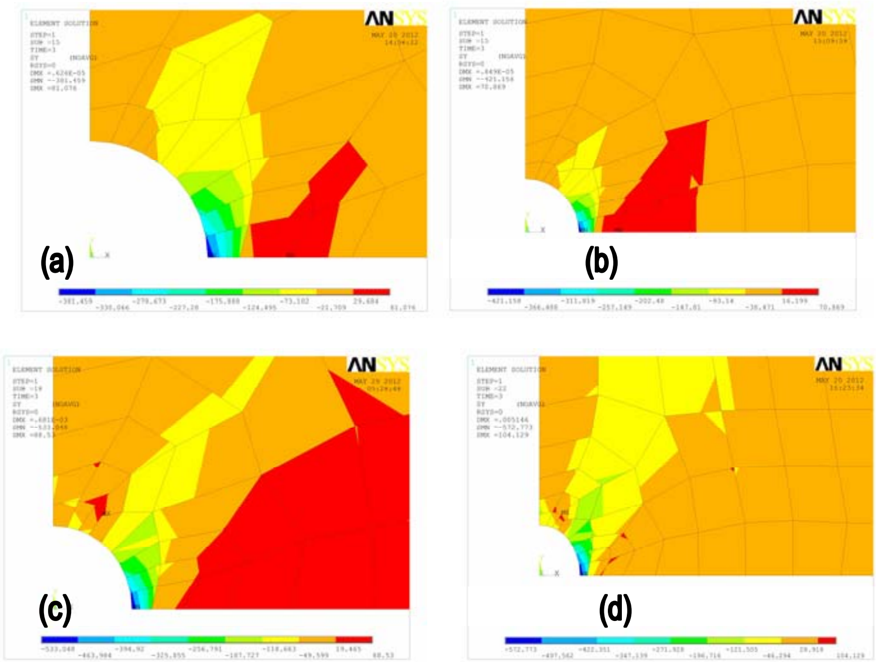

Figure 6. Stress contour for preload levels σ_p/σ_y for 2024 T351: (a) 1.047; (b) 1.102; (c) 1.212 (d) 1.350

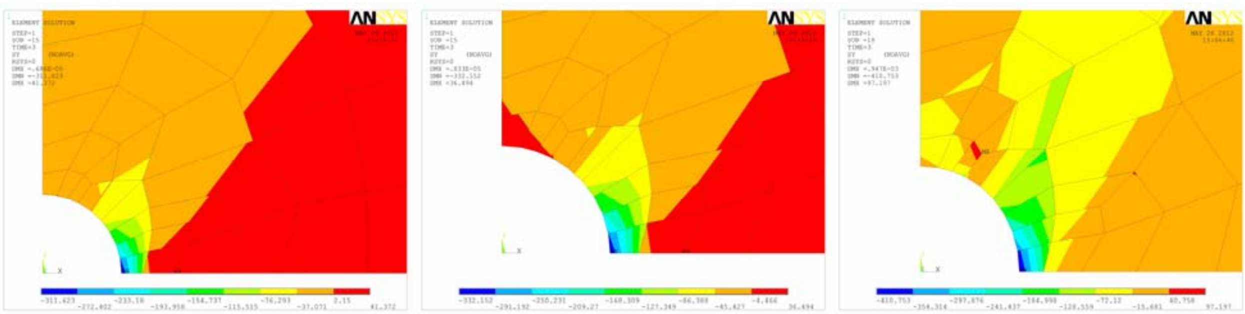

Figure 7. Stress contour for preload levels for 6061 T6 $\sigma_p/\sigma_{y:}$ (a) 1.19 ; (b) 1.23 ; (c) 1.39

Figure 8 shows variation of residual stress distribution σ_{yy} along X-axis for 2024 Al-alloy at different preload levels. Residual stresses are in compression state up to a depth of 1.57 to 1.72 mm from the edge of the hole. It shows an increasing of compressive residual stress with increasing of preload levels at hole. Around distance of 4.5 mm, residual stresses become tensile stresses and difference is negligible. Distributions of residual stresses σ_{yy} along X-axis for 6061 T6 Al-alloy at specified preload levels, are shown in figure 9. No high difference of residual stress at edge of hole was shown. The residual stress in tension is maximal at 2 mm deep from the edge of the hole still; it is of the order of 30 MPa.

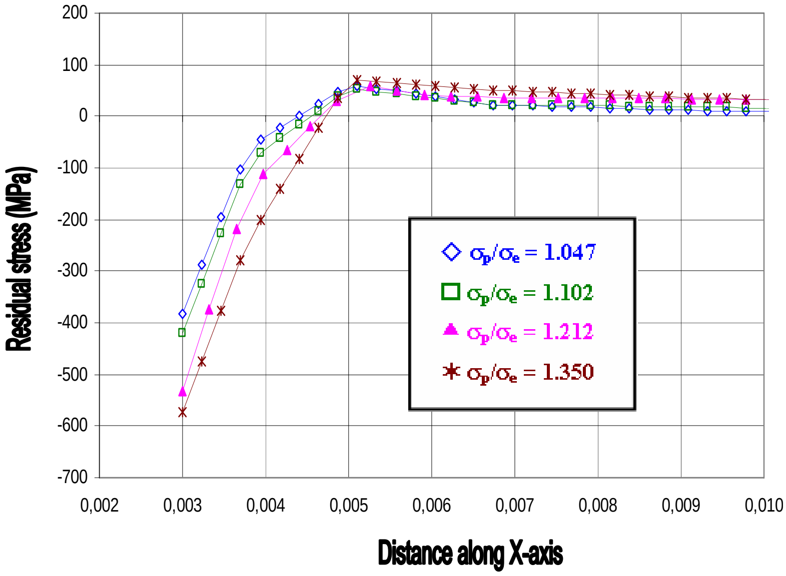

Figure 9. Residual stress along X-axis for 2024 T351 Al-alloy

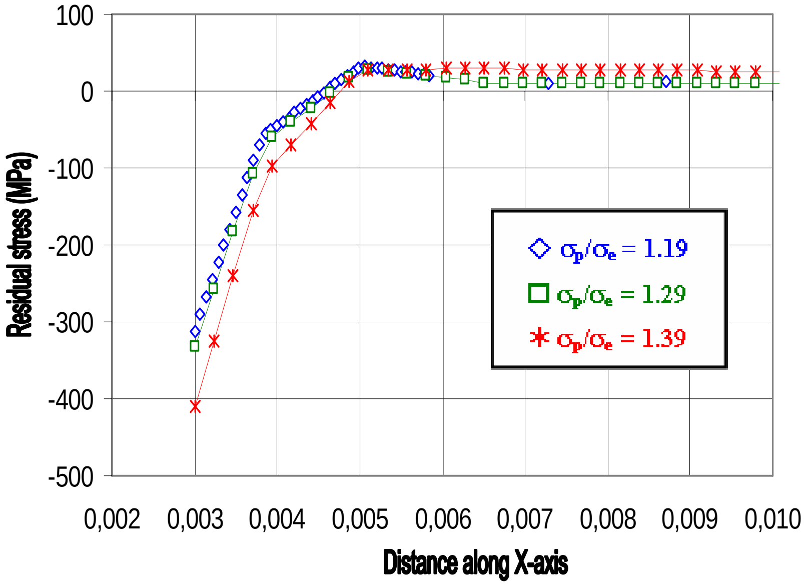

Figure 10. Residual stress along X-axis for 6061 T6 Al-alloy

3. Results and discussion

3.1. Fatigue crack growth modeling

The stress intensity factor for the studied specimen implemented in AFGROW code depends on several parameters and is given by Eq. 1.

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

where β is the geometry correction factor 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: $\lambda = 1/(1+(a/r))$

The interest model is NASGRO model when totality of fatigue crack growth curves is considered. Nasgro model are expressed bellow (Eq. 3):

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

f present the contribution of crack closure and the parameters C, n, p, q were determined experimentally and ΔK_{th} is the crack propagation threshold value of the stress–intensity factor range. For constant amplitude loading, the function f was determined by Newman [28] (see Eq. 4).

$$f = \frac{K_{op}}{K_{\max}} = \{\mathrm{Max}\left(R, A_0 + A_1 R + A_2 R^2 + A_3 R^3\right) \quad R \geqslant 0 \quad (4)$$

Crack growth parameters of Nasgro model for both materials are presented in Table 3.

Table 3. Parameters of Nasgro model for Al-alloys

Al-Alloy	ΔK_{tho} $MPa\sqrt{m}$	K_{IC} $MPa\sqrt{m}$	K_C $MPa\sqrt{m}$	n	p	q	C
2024 T351	2.857	37.36	74.72	3	0.5	1	1.707×10^{-10}
6061 T6	3.846	28.57	50.0	2.3	0.5	0.5	0.840×10^{-10}

3.2. Residual stress effect on fatigue crack growth

The variation of the fatigue crack growth rate (FCGR) as a function of the amplitude of the stress intensity factor ΔK through residual stresses fields obtained for different preload levels for 2024 T351 Al-alloy is shown in Figure 11. The result shows that FCGR depends on the magnitude of the compressive residual stresses developed at edge of hole.

We note that the FCGR increases while decreasing the preload level. At preloading level σ_p/σ_y equal 1.350, FCGR is about 1.6×10^{-9} m/cycle to crack initiation; against by a low level ie at σ_p/σ_y= 1.047, the FCGR is 1.75×10^{-7} m/cycle. This reduction is influenced by the decrease in residual stress intensity factor K_r whose variation is shown in Figure 12. Factor K_r past from -13.83 $MPa\sqrt{m}$ to -4.65 $MPa\sqrt{m}$. In absence of residual stress, FCGR is about 3.83×10^{-7} m/cycle.

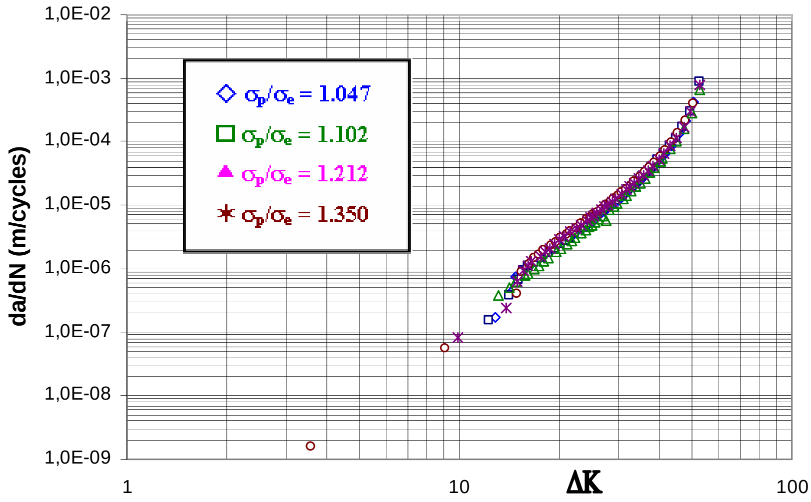

Figure 11. Preload levels effect on FCGR for 2024 T351 Al-alloy at R=0.25

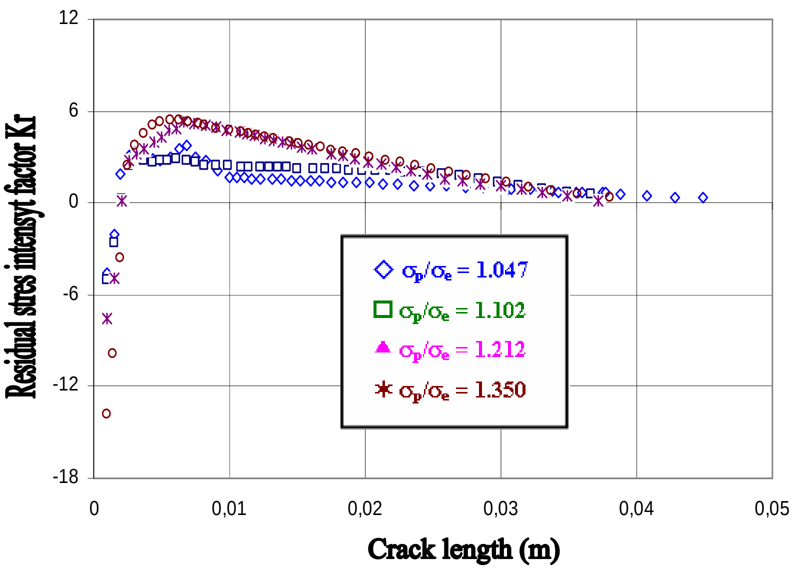

Figure 12. Variation of residual stress intensity factor Kr for preload levels of 2024 T351 Al-alloy

Residual stress effect on FCGR for 6061 Al-alloy is shown in figure 13. Their effect was significant at early cracking when residual stresses are is compressive state. Comparatively to state without residual stress, FCGR for level σ_p/σ_y equal to 1.19 was increased by 30%. For high preload level, σ_p/σ_y=1.37, FCGR was increased by 28.6%. The increasing of FCGR was linked to the decreasing of factor Kr when his variation was shown in figure 14. From 3.37 mm of crack length, residual stress intensity factor at σ_p/σ_y=1.37 is greatest to the other levels. This increasing was due to the presence of tensile residual stress at this area from 3.37 to 20 mm. The effect of residual stress was explained by the variation of stress ratio at any cycles for specified crack length.

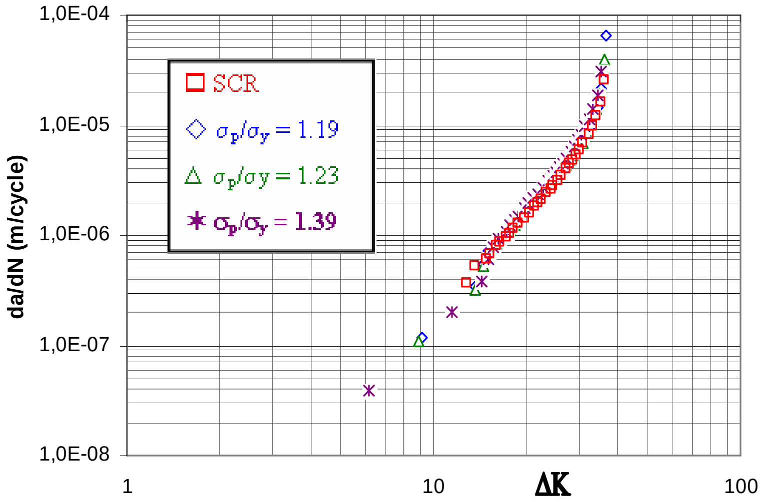

Figure 13. Preload levels effect on FCGR for 6061 T6 Al-alloy at R=0.25

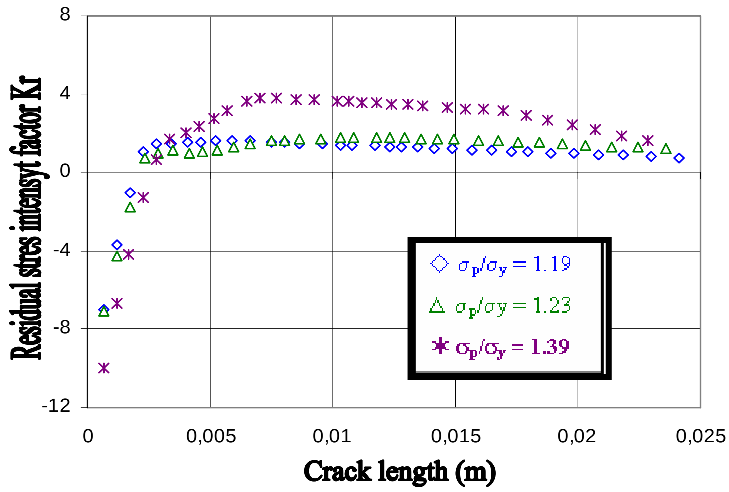

Figure 14. Variation of residual stress intensity factor Kr for preload levels of 6061 T6 Al-alloy

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