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Cold expansion effect on the fatigue crack growth of Al 6082: numerical investigation

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Abstract. Cold expansion is an efficient way to improve the fatigue life of an open hole. In this paper, three finite element models have been established to bind the crack growth from an expanded hole and simulated. Expansion and its degree influence are studied using a numerical analysis. Stress intensity factors are determined and used to evaluate the fatigue life. Residual stress field is evaluated using a nonlinear analysis and superposed with the applied stresses field in order to estimate fatigue crack growth. Experimental tests are conducted under constant loading. Results of this investigation indicate expansion and its degree are beneficial to fatigue life and a good agreement was observed between FEM simulations and experimental results.

Keywords: crack growth; cold expansion; residual stress; finite element method; fatigue life

1. Introduction

The fatigue life improvement of cold expanded fasten holes is attributed to the presence of compressive residual stress induced by cold expansion. The fatigue fracture of fasten holes account for 50-90% of structure fracture of aircrafts. Over the last 40 years, because of its simple realization and remarkable enhancement of the fatigue life of holes (usually 3-5 times than that of holes without cold expansion), the cold expansion process has been widely used to improve the fatigue life of components with fasten holes (Liu *et al.* 2010).

The cold-expansion, which is developed by the "Fatigue Technology Inc. (FTI 1994), is obtained by using increased pressure to plasticize an annular zone around the hole. The pressure on the surrounding material is realized by interference generated between the drilled plate and the pressuring element, i.e., the mandrel. When the mandrel is removed and the superficial pressure on the hole is erased, a residual stress field is created due to action of the elastic deformed material on that under plastic condition (Nigrelli 2008).

Cold expansion can be achieved in several different ways. A common feature of most methods is to insert an oversized object from one side of the holed plate and remove it from the other side.

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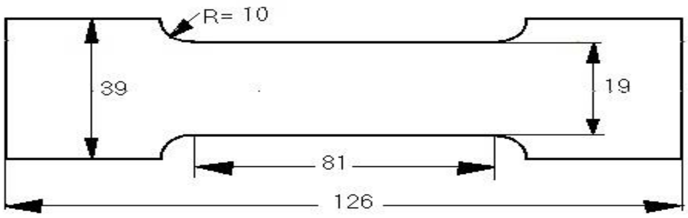


Fig. 1 Tensile Specimen geometry (all dimensions are in mm)

The main differences in methods relates to the shape of the oversized object and whether a sleeve is used in the hole during cold expansion (Amrouche *et al*. 2003, Bertrand and Fabrice 2005, Stefanescu *et al*. 2004, Toparli and Aksoy 1997, Pasta 2007, Zhang and Wang 2003, Wang and Zhang 2003, Lacarac *et al*. 2001, Gopalakrishna *et al*. 2010, De Matos *et al*. 2005). Compressive residual stress around a hole is very beneficial at resisting fatigue because it reduces the resultant stress at the critical edge of hole location when the plate undergoes a tensile load (Chakherlou and Vogwell 2003). In this paper, the results involves in first part, on experimental analysis to investigate the effect of cold expansion on fatigue crack growth in aluminum alloy. Numerical studies were carried out in order to identify the fields of compressive stress at the hole due the cold expansion process and to validate the FEM model.

Normally, strong winds have been associated with two types of wind in typhoon prone region. The first one is the nature wind and the other one is the typhoon, or say severe tropical cyclone. Many investigations about the vibration and buckling (static stability) characteristics of frames of various types have been carried out. Cheng (2011) have studied the elastic critical loads for plane frames by using the transfer matrix method. A general digital computer method has been described by Cheng and Xu (2012).

2. Experimental and numerical model

2.1 Experimental procedure

The experimental part of this work is subdivided into three steps: Tension test, fatigue test and inducing residual stresses by cold expansion.

2.1.1 Materials and specimens

Aluminum alloy 6082-T6 from 8.0mm thickness was used in this investigation (Fig. 1). Tensile specimens were machined with the dimensions and geometry as specified by the ASTM B557-06 designation. The quasi-static tension test was performed with a head speed displacement of 0.02 mm s-1. Tensile strain of specimens was measured with an Instron® extensometer model 2620-601.

The mechanical properties and chemical compositions of this material were presented in Tables 1 and 2, respectively.

2.1.2 Fatigue tests and cold expansion

Specimens were cut from aluminum alloy plates of 8mm thick plate, with the axis parallel to

Table 1 Mechanical properties of test material

Alloy	σ_y (MPa)	σ_R (MPa)	E (GPa)	Elongation
6082A T6	280	327	68	12%

Table 2 Chemical compositions of material

Alloy	Mg	Si	Fe	Cu	Mn	Cr	Zn	Ti
6082A T6	0.60	0.7	0.24	0.06	0.9	0.02	0.06	0.02

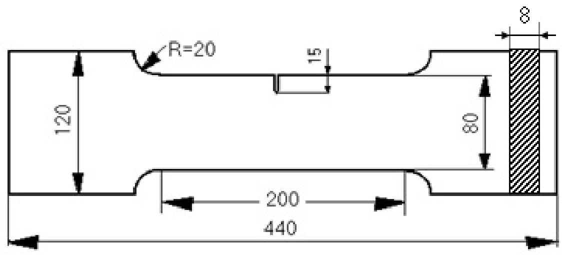


Fig. 2 Fatigue Specimen (SENT) (all dimensions are in mm)

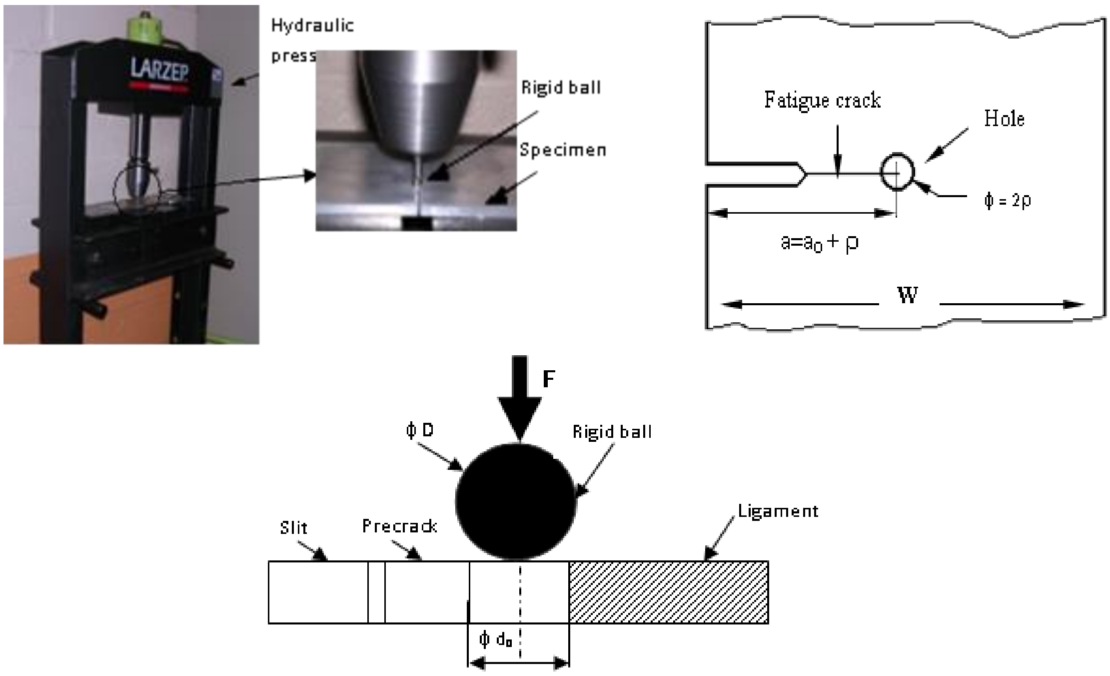


Fig. 3 Cold expansion process.

the rolling direction of the plate. The SENT (Single Edge Notch Tension) specimen configuration used for the experiments is taken from the ASTM E647-95 [E647-95]. The dimensions of the specimen are shown in Fig. 2.

A slit of 1mm in width and 15 mm in length was machined at one lateral side of the specimen. A pre crack from the slit tip was introduced by cyclic loading and the total length of the slit and the pre crack was ($a0+\rho$ where $\rho=d/2$), the distance from the crack tip is equal to a where $a=a0+\rho$ and ρ is radius of the hole. A hole was drilled at the pre crack tip. The hole was firstly drilled conventionally and then carefully enlarged by a boring bar to a desired radius. The cold working expansion process was realized by forcing a hard steel ball of 6 mm inside a predrilled hole (the initial diameters of the hole are: 5.9, 5.8 and 5.75mm; see Fig. 3).

The degree of expansion is calculated as follows (Amrouche *et al.* 2008)

$$DCE\% = \frac{D - d_0}{d_0} \times 100 \tag{1}$$

There are 3 DCE applied: 17%, 34% and 43% (Amrouche *et al.* 2008, Bendouba *et al*. 2012).

Fatigue tests were conducted using constant amplitude loading. Load ratio, $R = \sigma\text{min}/\sigma\text{max}$, is 0.57, where σmax and σmin are the maximal and minimal loading. Hydraulic machine INSTRON 8501 was used at a frequency of 30 Hz. During fatigue testing, a video camera with a least count 0.1mm was used to determine the crack initiation and propagation in the entry and exit faces of specimen.

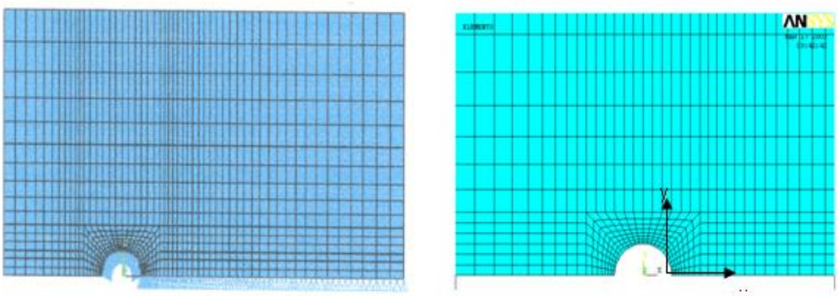
2.2 Finite element simulation

Three finite element models were used to analyze and simulate the crack growth using the commercial code ANSYS. The effect of an expansion bya rigid ball through the thickness of the plate on the hole was checked.

A two-step simulation was performed, in order to numerically analyze the effect of cold expansion on the crack growth:

First, the modelisation of cold expansion was carried out by pushing the rigid ball on the *Z*-direction, through the hole and removed from the other side by applying displacement increments on the surface nodes of this latter. Cette phase représente la création du champ de contrainte résiduelle le long du trou et la zone voisine. After this, there is a relaxation of the compressed zone due to the elastic recovery of the total strains.

The second step consists in applying remote longitudinal stresses, this step allow simulate the loading process during the fatigue tests.



(a) Specimen and ball (expansion) (b) Mesh for expansion and propagation

Fig. 4 Finite Element Mesh

Fig. 4 shows the finite element mesh. Taken into account the symmetry of loading and geometry, only the half of the model is studied in order to reduce the calculation time. Three dimensional solid elements with eight nodes were used in this work. The mesh is denser around the hole (expansion) and on the way of crack propagation.

The same mesh was used to simulate expansion and propagation. An elastoplastic material relationship was used to represent the aluminum alloy 6082A T6 behavior. The theory of incremental plasticity is introduced to modeling the material nonlinearity. The iterative method of Newton-Raphson is used as an approach to solve nonlinear equations by finite elements.

3. Procedure to estimate the fatigue life

Superposition techniques are often used when assessing the effects of a known residual stress field on fatigue crack propagation. To estimate crack growth from equation, some authors (Rich and Impellizzeri 1977, LaRue 2005, Chobin *et al*. 2009, LaRue and Daniewicz 2007) compute a stress intensity factor which is associated with the initial pre-existing residual stress field (K_{res}). This factor it then superimposed upon the stress intensity factor that results from external loading (K_{app}) to give the total resultant stress intensity factor for the maximum and minimum loads

$$K_{max} = \left(K_{max}\right)_{app} + K_{res}, \qquad K_{min} = \left(K_{min}\right)_{app} + K_{res} \tag{2}$$

Stress intensity range is then calculated using:

$$\Delta K = K_{max} - K_{min} = \left(K_{max}\right)_{app} - \left(K_{min}\right)_{app} \tag{3}$$

Where $(K_{max})_{app}$ and $(K_{min})_{app}$ correspond to maximal and minimal applied load consecutively.

According to these authors, stress intensity range is independent on residual stresses and only stress ratio (R) is affected.

$$R = \frac{K_{min}}{K_{max}} \tag{4}$$

Total stress σ_T induces a displacement of crack face. Given this displacement value and assuming fracture mode one, ANSYS calculate total stress intensity factor with Irwin theory (Keith and Martin 2009)

$$K_T = \sqrt{2\pi}\,\frac{2G}{1+\kappa}\,\frac{|v|}{\sqrt{r}} \tag{5}$$

Where G is shear modulus; κ is equal to (3-4ν) if plane strain is assumed and to (3ν/(1+ν)) in plane stress; ν is Poisson's ratio; v displacements in local Cartesian coordinate system as shown in Fig. 5.

According to Eqs. (3) and (4), stress intensity range is calculated as follows

$$\left(K_T\right)_{min} = R.\left(K_T\right)_{max} \tag{6}$$

$$\Delta K_T = \left(K_T\right)_{max} - \left(K_T\right)_{min} \tag{7}$$

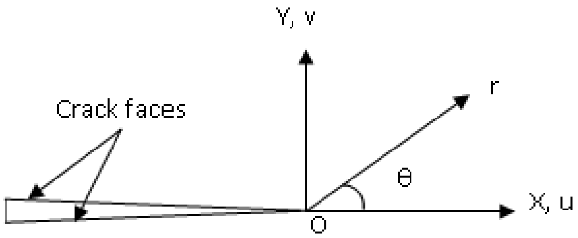


Fig. 5 Crack tip Local coordinate system

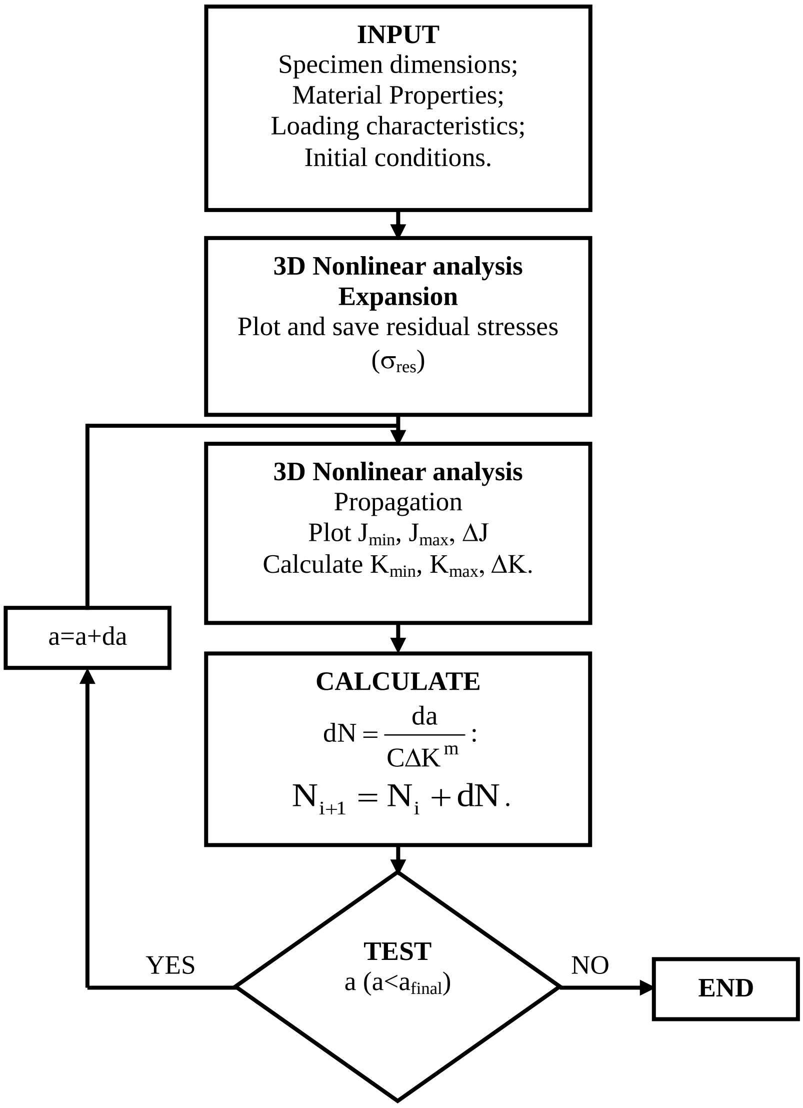


Fig. 6 Procedure to estimate fatigue life

Crack growth depends also on load ratio (ANSYS 2007, Kusko *et al*. 2004, Kujawski 2001). This effect is introduced by Eq. (5). We take a value of load ratio that minimizes the effect of crack opening, this, allows using Paris law to evaluate crack growth rate.

$$\frac{da}{dN} = C\Delta K^{m} \tag{8}$$

Where, *da/dN* represents the increment of the crack growth per cycle.

Many authors use superposition technique (Newman 2000, Ramesh 2005). This use has been criticized by some researchers because it doesn't take in consideration residual stresses relaxation during crack propagation (Underwood *et al.* 1977, Fukuda and Tsuruta 1978, Chandawanich and Sharpe Jr. 1979, Lam and Lian 1989). In the present work this effect won't be taken in count. Macro files were implemented to simulate crack propagation, using Paris law, under residual stresses influence; this is not possible to do directly in this simulation tool. Calculation procedure is represented in Fig. 6.

a_{final} represents the final value of crack length at which calculation will be stopped.

As shown in this figure, Ansys software was used to calculate *J*-integral. This method has the advantage of keeping the same mesh of the specimen during crack propagation. Stress Intensity Factors, assuming fracture mode one, are calculated using Eq. (9) and Eq. (10).

$$K = \sqrt{E' \times J} \tag{9}$$

With

$$\begin{cases} E' = E & \textit{plane stress} \\ E' = \dfrac{E}{1-\nu^2} & \textit{plane strain} \end{cases} \tag{10}$$

4. Results and discussions

4.1 Validation of the finite element analysis

Fig. 7 compare the experimental and finite elements results in three cases of the degree of cold expansion (DCE): DCE = 1.7%, 3.4% and 4.3% applied to 6 mm hole diameter.

A first observation from the reading of Fig. 7 is that whatever the degree of cold expansion DCE, the crack length affects significantly on the life time *N*. Indeed, this life time *N* increases proportionally with the crack length and its variation takes an exponential evolution if the crack is higher whatever the value of DCE. According to the experimental and numerical analysis, it can be seen that the result gave a good correlation between various methods, thus establishing confidence in the results of the finite element modeling for cold expansion process.

We observe a large influence (DCE) on life. The life increases proportionally with the DCE. This finding is more evident when the DCE reaches 4.3% where life goes from 1.57E6 cycles for DCE equal to 1.7% to 2.58E6 cycles for DCE equal to 4.3%. Initial life time was increased by a factor of approximately 2.

This latter finding is due to the presence of residual strains, which are beneficial for the life of structures repaired by cold expansion method.

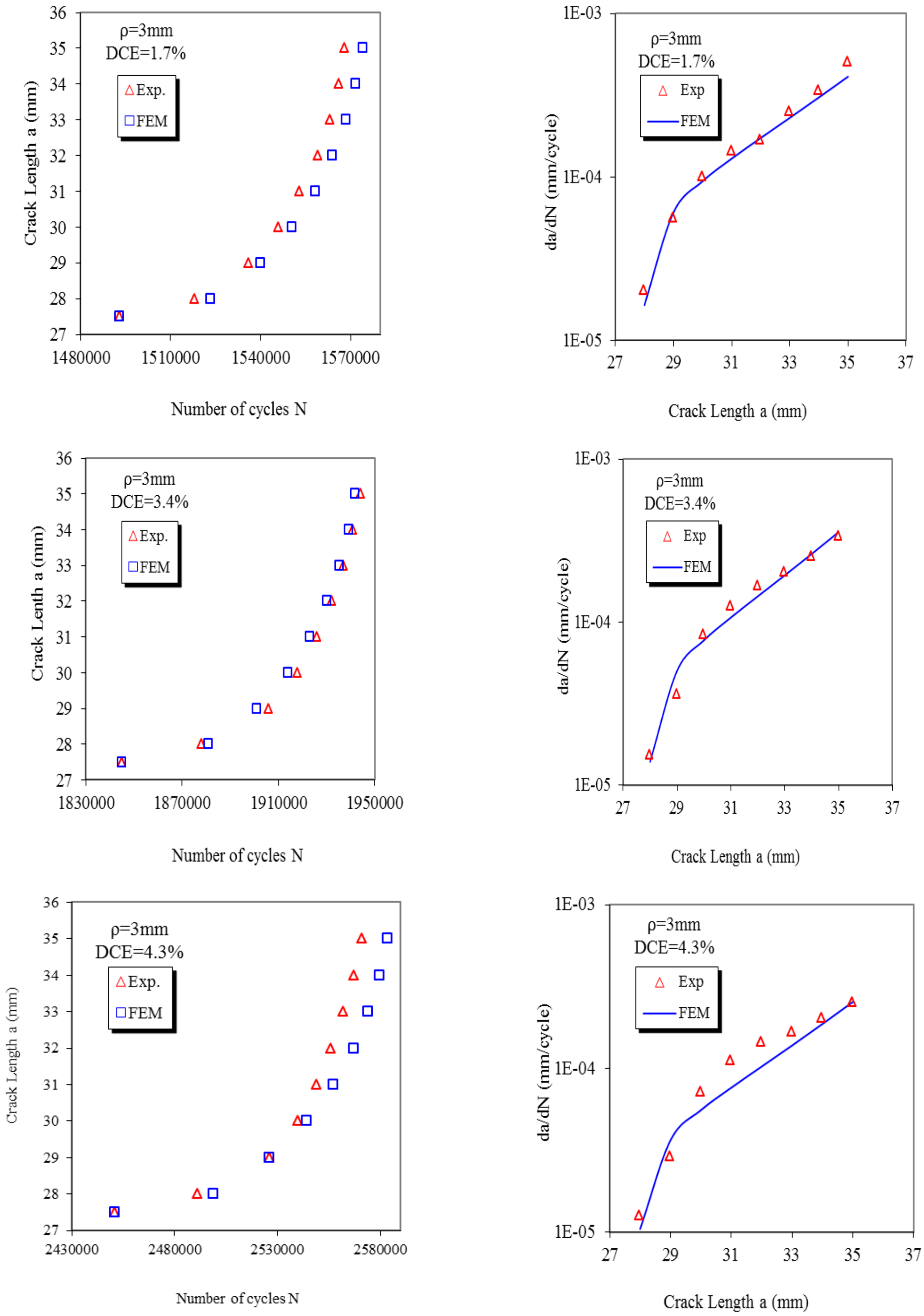


Fig. 7 Comparison between experimental and finite element results

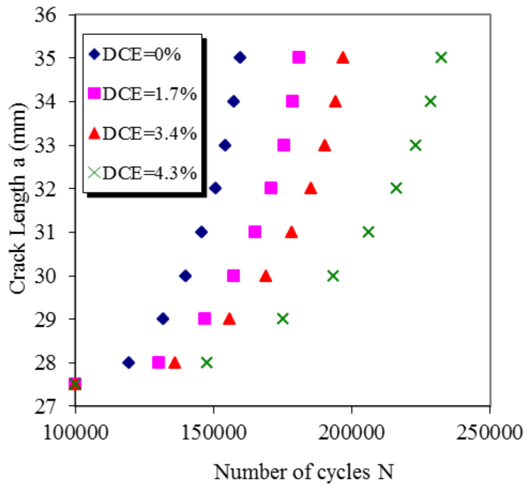


Fig. 8 Improvement of fatigue life by expansion

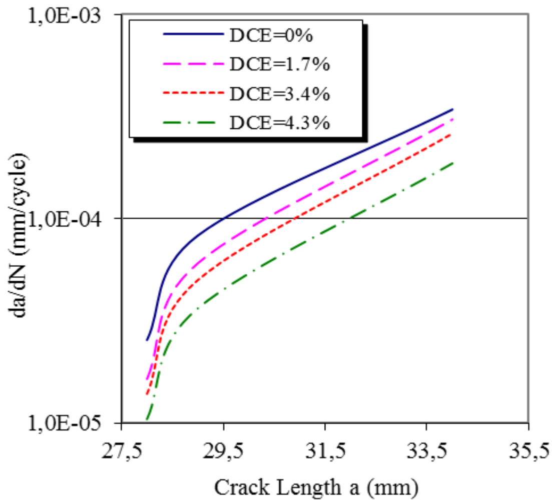


Fig. 9 Effect of expansion degree on fatigue crack growth rate

Finite element simulation results shown in Fig. 7 are in good correlation with the experimental results.

4.2 Effect of cold expansion

The effect of expansion and the increase of DCE is illustrated in Fig. 8.

Four degrees of expansion are applied to a hole of 6mm diameter. DCE equal to zero correspond to a hole without expansion (fatigue plane). The initial number of cycles, corresponding to the Initiation of the crack, is taken equal to 1E5 cycles. This is not true because expansion have also an effect on initiation phase, this result were confirmed by other research

(Todoroki and Kobayashi 1991, Man 2005). The expansion improves fatigue life due to the existence of residual stresses on the side of the hole. This field of stresses tends to decrease crack growth rate as shown in Fig. 9.

5. Conclusions

The aim of this study is to analyze the effect, by finite element method investigation, the effect of cold expansion process on the crack growth in aluminum alloy, from experimental and numerical results; it can be deduced the following conclusions:

• The ability of cold expansion to produce beneficial compressive residual stresses around fastener holes was numerically investigated in this work. Stress superposition technique was applied to plot stress intensity factors by finite element in ANSYS. This analyze tool was implemented in order to plot SIF (Stress Intensity Factors) during crack propagation.

• Expansion process was simulated with a nonlinear analysis. Residual stresses were superposed to the applied stress field and the resulting stress intensity factors were calculated for each crack length. Crack propagation phase was done considering only the linear behavior of the studied aluminum alloy.

• Simulation results are in good agreement with experiment's data. This confrontation demonstrates the benefit that has expansion and its degree DE on crack propagation.

• Other works are conducted to see the effect of residual stresses on Kmin, Kmax and ΔK separately. The redistribution of residual stress field during the initiation and the propagation of the crack and the numerical determination of the optimal value of expansion degree are also under study.

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