Effect of residual stresses and their redistribution on the fatigue crack growth in cold-worked holes

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ABSTRACT. The cold-expansion process is widely used to enhance the fatigue life of structures with fastener holes. Various studies assert that the cold-expansion improves the fatigue strength of fastener holes; however, the improvement of fatigue life is difficult to quantify. The influence on fatigue life of cold-worked hole in a 6061-T6 aluminum allosy was studied by numerical and experimental tests. Fatigue crack growth tests were carried out to find the crack length and growth rates of crack propagating from hole edge. Thus, the cold-expansion process was modeled with a Lagrangian implicit code for metal forming to obtain the residual stress field. Progressive crack growth along the observed fatigue path was simulated as part of the analysis to observe the residual stress redistribution due to the crack propagation. The behavior of a fatigue crack in the presence of the hoop residual stress is discussed.

INTRODUCTION

Fatigue crack growth in aircraft and naval components originates from stress concentration such as that produced by a fastener hole. Consequently, a cold-worked process has been used for over 25 years as standard technique to delay the propagation of fatigue cracks. The cold-worked process introduces beneficial residual circumferential stresses into an annular region around the hole; the presence of this compressive residual stress inhibits the growth and propagation of cracks. In fact, the effect of residual stress may be explained using a fatigue-crack closure model in which compressive residual stress reduces the effective stress intensity factor, i.e. the crack growth rate.

The cold-expansion developed by the Fatigue Technology Inc., FTI, [1] is obtained by using increased pressure to plasticize an annular zone around the hole, Fig. 1.
Figure 1. Sketch of the split-sleeve cold-expansion process developed by FTI

The pressure on the surrounding material is realized by interference generated between the drilled plate and pressuring element, i.e. the mandrel. Such interference causes a stress state which decreases with increasing distance from hole edge. When the mandrel is removed and the superficial pressure on the hole is erased, a residual stress field is created due to the action of the elastic deformed material on that under plastic condition. A split sleeve is introduced to reduce the shear of the material surrounding the hole and to ensure radial pressure on the plate; however, the opening of the split in the sleeve distributes hoop residual stresses asymmetrically.

Analytical studies can be used to determine the closed-form solution of the hoop and radial residual stresses by considering the material’s yield limit on unloading step [2-5]. However, most of these solutions are based on two-dimensional approximations, and theories are not able to predict the through-thickness residual stress changes. Therefore, these solutions would predict fatigue life non-conservatively. Fatigue crack growth tests coupled with AFGROW analyses [6] show that the fatigue life for a 4% expansion level is improved with respect to plain hole, and that the material properties can affect the fatigue life significantly. Finite element (FE) analyses [7-8] take advantage of the symmetry of the drilled plate in order to model only a fourth of the model. Consequently, these analyses neglect the effect of the opening of the split in the sleeve and show uniform distribution of residual stresses. A recent analysis [9] highlighted that at pip location of the split sleeve, the hoop residual stress is significant lower than that at 90° from the pip. The most important experimental technique for evaluating the residual stress is Sach’s boring [10]. A recent study [11] shows how optical methods can be used to determine the radial displacement on the inlet surface to correlate with the plastic radius.

The objective of the current investigation is to characterize the fatigue behavior of a 6061-T6 cold-worked hole. The fatigue life and crack growth rate curves were obtained for a nominal 4% expansion level on specimens having thickness of 3mm. Thus, the cold-expansion process was simulated with an implicit code to obtain the hoop residual stress profile. A crack growth was simulated to observe the stress redistribution at crack tip due to crack growth propagation. It has been noticed that the magnitude of hoop residual stress decreases as the crack length improves; as a consequence, the growth rates increases.
FATIGUE TESTS

Fatigue crack growth tests were performed by a servo-hydraulic MTS testing machine with a 100kN load cell. The fatigue specimens were obtained from a 3mm thick alloy plate, the dimensions of which are shown in Fig. 2:

![Figure 2. Shape and dimensions of fatigue test specimens](image)

The $FTI$ process was used to expand at 4% nominal interference, $I$, several fatigue specimens. For fatigue tests, the loading frequency was 10Hz, while the stress ratio was chosen as $R=0.1$. Crack growth length was monitored on both sides of the hole edge by means of high-resolution digital images and clip-on gage. Specimen compliance and loads were regulated using *MTS Fatigue Crack Growth* software. The crack growth rates were determined by measuring the first crack length recognizable from digital image.

The Wöhler’s curves were achieved for cold-worked specimens and for the plain hole, Fig. 3:

![Figure 3. Fatigue curve for cold-worked holes at $I=4\%$ and plain hole](image)
The cold-worked process always improves the fatigue life, compared to the strength of the plain hole. Moreover, the effect of cold working is highlighted at a higher number of cycles. The number of cycles to fracture of the plain hole at the same stress level is always lower than the number of cycles to fracture of cold-worked holes.

The crack length as a function of the number of cycles was derived by processing the digital images and compliance data obtained with clip-on gage, Fig. 4. Two different cracks develop on the right (dx) and on the left (sx) of the hole; thus the crack length curves for both cracks are showed separately. The crack length curves are shown for 4% nominal interference and plain hole for two stress levels, $P_{\text{max}}$.
Fig. 4 shows an improvement of stable crack propagation for both stress levels before fracture. The variation of the slope of the crack length curve is correlated with the values of the stress intensity factors present at the crack tip. In fact, the compressive residual stress diminishes the effective stress intensity factors, i.e. reduces the crack growth rate. When the crack propagates within the tensile residual stress field, the residual stress intensity factor cumulates with the effective stress intensity factor, considerably enhancing the slope of the crack length curve.

Fig. 5 shows the crack growth rate vs. $\Delta K_I$ stress intensity factor range for plain hole and cold-expanded hole at 4% nominal interference:

Figure 5. Crack growth rate curves for plain hole and 4% expansion level

It can be noticed from Fig. 5 that the Paris’ curves for plain and expanded hole cross each others at $\Delta K_I=22$ MPa m$^{1/2}$, approximately. Below this points, the crack growth rates for cold-worked holes are lower than those of plain hole specimens for the same $\Delta K_I$ value. Over this point, differently, the growth rates for cold-worked holes are higher at the same $\Delta K_I$ value. Therefore, it should be believed that in this point the hoop residual stress, which tends to close the crack tip, changes from compressive to tensile.

FINITE ELEMENT REDISTRIBUTION OF RESIDUAL STRESS

The 3D numerical analysis was carried out simulating the cold-expansion process of a 6061-T6 aluminum plate at 4% nominal interference. The simulation permits to obtain the residual stress distribution due to FTI process.

All objects of the cold-expansion process were simulated in this research, Fig. 6.
The split sleeve was considered elastic, while the mandrel and the support were assumed to be rigid bodies. The material behavior of the plate was considered with an elasto-plastic model. The elastic data were introduced by adding the Young’s modulus \(E=68900\text{MPa}\) and Poisson’s ratio \(\nu=0.3\) whereas the plastic domain was considered filling the strength coefficient and strain-hardening exponent of the 6061-T6 aluminum alloy. A kinematic hardening model using a Bauschinger’s parameter equal to 1 was assumed. The dimension and shape of the plate reflect those of fatigue specimens. Tetra elements with four nodes were used for the mesh of the plate and split sleeve (see Fig. 6). The element size was improved at the hole edge. During the mandrel movement, the remeshing was automatically calculated to conveniently handle the remeshing of objects undergoing large plastic deformation. The boundary contact conditions among objects were expressed with contact elements. During the process, the contact elements are automatically drawn. The mandrel speed was 4mm/min. The coefficient of friction was assumed to be equal to 0.3. The loading and unloading were simulated through a total of 315 steps with mandrel increments equal to 0.2mm. Since DEFORM-3D™ does not allow to delete elements in order to simulate the crack growth propagation, the mesh and residual stress field were extrapolated and imported to ANSYS® code. The node position, element number, and residual stress tensor for each element were extrapolated and trasfered through a MATLAB alghoritm in a similar ANSYS® model. The crack growth propagation was carried out using low elastic modulus of elements representing the crack front.

Fig. 7 shows the hoop residual stress redistribution, which is significant in crack growth, as a function of crack length in case of a single and two through cracks at hole edge:
Fig. 7(A) and (B) shows that the magnitude of hoop residual stress decrease as the crack length improves. Although the positive peak of the hoop residual stress remains unaffected by the crack propagation; the magnitudes of the compressive stresses decrease significantly with the crack length. It can be also observed that the hoop residual stress becomes positive when the crack length is 4mm, approximately; moreover, the positive peak is lower than that shown in absence of a crack. Therefore, the redistribution of the hoop residual stress would have to increase the stress intensity factor at crack tip with consequent improvements of the crack growth rates. A slight difference in the magnitude of redistributed residual stress has been noticed for the cases of two symmetric-through cracks Further investigations will be performed to obtain the crack length curves with AFGROW software in the presence of the redistributed residual stress to compare with experimental tests.
CONCLUSIONS

In this work, the fatigue crack growth propagation from a cold-worked hole has been studied with experimental tests and numerical analyses. Initially, the fatigue life for holes expanded to a 4% nominal interference was compared to that of plain hole. The fatigue tests show a significant improvement of the fatigue life of worked holes with respect to those of plain holes. This result is mainly due to the effect of compressive hoop residual stress induced by FTI process that acts to reduce the effective stress intensity factor at crack tip, i.e. the crack growth rate. The crack length curves have highlighted a significant enhancement of number of cycles to fracture for cold-worked holes at the same load level. It has been noticed that the Paris’ curves for plain and worked hole cross each others in a point representing the changes from compressive to tensile hoop stress. Below this point, indeed, the growth rates for cold-worked hole are lower whereas, over this, they are higher than those of plain holes for the same applied $\Delta K_I$. Then, the FTI process was modeled to obtain the hoop residual stress around the hole, and progressive crack growth along the observed fatigue path was simulated as part of the analysis to observe the hoop residual stress redistribution due to the crack propagation. The FE analysis has shown how the magnitudes of the compressive stresses decrease significantly with the crack length; consequently, it should produce higher crack growth rates. It has been also observed that the hoop residual stress becomes positive for high crack length. This redistributed residual stress will be used in AFGROW software to simulate the crack growth to be compared with the experimental tests.

REFERENCES