Observations and Analysis of Fatigue Crack Growth from Cold Expanded Holes

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Abstract:

The split-sleeve cold expansion process of Fatigue Technology Inc. (FTI) has been used for over 35 years by the aircraft industry to improve the fatigue life of structures by inducing compressive residual stresses around holes. Current methods of predicting the fatigue life and crack growth from cold expanded holes demonstrated a lack correlation between the predicted and actual crack growth and have also been shown to be very sensitive to possible errors. Since a good correlation of the predicted and real crack growth is essential to an accurate and efficient damage tolerance program, the applicability and effectiveness of the current method is questionable. A preliminary three-dimensional investigation into the crack mechanics indicated that the crack front shape of a cold expanded hole was distinctly different than crack growth from a non cold expanded hole. A series of fatigue tests of 7075-T651 open hole dogbone specimens were run to investigate the crack front shape. The results showed that the crack front shape was significantly different from a cold expanded hole than a non cold expanded hole and varied some with thickness. The distinct P shaped crack front shape was investigated further by growing a crack from a cold expanded hole in a 3-D Finite Element Analysis (FEA) Model. At this stage in the development of the model, CTOA was used as an indicator of relative speed of crack growth in various directions rather than associating it with an absolute crack growth rate. The model showed a similar crack front shape via the simple CTOA criterion as the experiments due to the complex thru thickness residual stress distribution. This thru thickness distribution was the cause for the P shaped crack and the faster crack growth observed on the entry side than the exit side surface of the cold expanded specimens. Because the crack front shape of a cold expanded hole is different than a non cold expanded hole, any prediction method is better served by accurately modeling the real crack growth rather than correlating the life with a model of a physical different crack shape with a slower crack growth rate.

Introduction:

The split-sleeve cold expansion process of Fatigue Technology Inc. (FTI) has been used for over 35 years by the aircraft industry to improve the fatigue life of structures by inducing compressive residual stresses around holes. The process is simple to perform with a mandrel with a prefitted lubricated split sleeve being pulled through the hole in the structure as indicated in Figure 1. The radial expansion of the hole results in plastic deformation. Once the mandrel is removed, an equilibrium stress state is established where the material that has been plastic deformed is in residual compressive hoop stresses while the surrounding elastic material is in residual hoop tensile stress. The
magnitude of the compressive residual hoop stress is large enough to result in a significant fatigue life improvement.

![Figure 1. FTI Split-Sleeve Cold Expansion Process](image)

The fatigue life benefit associated with the cold expansion process has been validated numerous times by both experimental testing and in-service. The challenge is to predict the fatigue life benefit without extensive testing. The most common method used today is a two-dimensional (2-D) stress intensity factor (K) solution using linear superposition of the K solutions for a non cold expanded hole (NCx) and for the residual hoop stress associated with cold expansion (Cx). This method can be summarized in Equation 1.

\[ K_{\text{non cold expanded}} + K_{\text{residual stress}} = K_{\text{effective}} \]  

\( (1) \)

Past studies by various authors have shown varying levels of success in predicting the overall fatigue life [1-4]. The correlation between the analytically predicted and experimental fatigue crack growth curves have not been considered. Those few studies that include the entire crack growth curve show that the 2-D K method tends to underestimate the fatigue crack lengths over the majority of the fatigue life. In practice, the level of agreement observed in these studies between the analytical predictions and the experimental crack growth curves may result in premature part replacement and erroneous inspection intervals. Since a large part of the fatigue life improvement occurs during the crack growth of small and intermediate cracks, it is essential that the current method be evaluated in terms of its ability to correctly predict the entire fatigue crack growth curve.

**FTI Past Work:**

FTI completed an earlier study into the ability of the current method to predict the overall crack growth curve of cracks growing from cold expanded holes. Several different tools
were used including an inverse analysis, experimental testing and two-dimensional (2-D) and three-dimension (3-D) finite element analysis (FEA). The results of this study are summarized below.

Analytical programs such as AFGROW are commonly used to predict or validate the fatigue life and fatigue crack growth curve. To apply the 2-D $K$ solution method using equation (1), $K_{\text{non cold expanded}}$ is obtained from a known solution for the geometry and $K_{\text{residual stress}}$ is typically determined via a weight function method to calculate $K_{\text{effective}}$ and $\Delta K_{\text{effective}}$. In the inverse iterative analysis, $K_{\text{residual stress}}$ is considered an unknown. As in the predictive analysis, $K_{\text{non cold expanded}}$ is obtained from a known solution. $K_{\text{effective}}$ is considered a known value calculated from the experimental crack growth rate and material data. $K_{\text{residual stress}}$ can then be calculated as shown in equation 2.

$$K_{\text{residual stress}} = K_{\text{effective}} - K_{\text{non cold expanded}}$$ (2)

The inverse iterative method is a very useful method for evaluating $K_{\text{residual stress}}$ and was applied to some of the experimental results published by Saunder and Grandt [5]. All the required information was included in the paper including material da/dn vs. $\Delta K$ data and the full experimental crack growth curve. The crack growth curve reported by Saunder and Grandt is given in Figure 2 for the data of interest. Figure 2 also shows the matching crack growth curve of the iterative analysis. In the experiment, different crack lengths were noted for the entry and exit sides of the hole but the averaged results were reported. Since the current method is 2-D based, the average crack length was used as in most other studies.

![Experimental Average vs. Afgrow Inverse Fit](image)

Figure 2. Experimental Crack Growth Curve from Saunder and Grandt[5] and AFGROW Inverse Analysis Results
The $K_{\text{residual stress}}$ required to match the crack growth curve of Figure 2 is shown in Figure 3. The most intriguing aspect of the $K_{\text{residual stress}}$ is a pronounced flat region that also corresponds to a large portion of the overall fatigue life. $K_{\text{residual stress}}$ obtained from weight function methods assume a similar shape to the residual hoop stress distribution obtained from FEA that is also shown in Figure 3 for this geometry. The sharp gradient in the residual stress distribution and the relatively low average value of the residual compressive stress corresponding to the flat region with large values in the inversely generated $K_{\text{residual stress}}$ were inconsistent with any predicted $K_{\text{residual stress}}$ solution. This is validated by published $K_{\text{residual stress}}$ curves that show a distinct, sharp peak consistent with the residual stress. The flat region generated by the inverse analysis was very important to replicating the slow stable crack growth that occurred over the majority of the fatigue life and the predicted solutions do not appear to include it.

During the inverse analysis, the slow crack growth associated with cold expanded holes in the region discussed in Figure 3 (short and intermediate cracks) was found to be extremely sensitive to the value of $K_{\text{effective}}$. In a predictive analysis, predicting the crack growth in this region would require a very accurate measure of $K_{\text{residual stress}}$ and the material behavior. The overall sensitivity of the 2-D method as a predictive tool was tested by arbitrarily modifying the $K_{\text{residual stress}}$ obtained from the inverse solution by +/-1% and observing the effect on the fatigue life and crack growth. As a result, the small modification of +/-1% resulted in under predicting the fatigue life by 26% and over predicting the fatigue crack growth by 38% as shown in Figure 4. This variance of +/-1% is considered to be a conservative estimate of the error associated with calculating $K_{\text{residual stress}}$ and the various material property data used in the predictive analysis. These results exposes one of the most distressing limitation of the current 2-D method, it’s extreme sensitivity to error.
The lack of agreement between the experimental crack growth curves and predicted curves, the differences between the inversely calculated $K_{\text{residual stress}}$ and the residual stress distribution and $K_{\text{residual stress}}$ from the literature and the extreme sensitivity of the predicted life indicated that the current 2-D method was missing important aspects of the crack growth from cold expanded holes. In an effort to evaluate what was missing from the current method, a 2-D FEA model of the test specimens was created to look at the physics of the crack opening during growth. The model was subjected to a uniform radial expansion and then allowed to relax followed by removal of elements corresponding to the ream operation. Cracks were “grown” by removing displacement boundary conditions at nodes along the crack plane and the resulting opening and closing of the crack under fatigue loading was observed for various crack lengths.

The results of the 2-D FEA indicated that the crack tip and a significant region of the crack remained closed when the crack was 0.008-inch to 0.074-inch in length as shown in Figure 5. This indicated that a crack would not grow whereas the experimental results plainly showed otherwise. As a result of these results and the failings of the 2-D prediction method, it was determined that a 2-D representation of the crack and crack growth was not representative of the actual cracks in his study growing from cold expanded holes.

Figure 4. Effect of +/-1% Error on the Predicted Fatigue Life From the 2-D K Method
Because of the failure of the 2-D FEA to adequately model the physics of the crack, a 3-D FEA model of the crack was created. In the 3-D model, the mandrel and sleeve were modeled explicitly and the mandrel was pulled through the sleeve and hole to generate the real distribution of stress thru the thickness rather than the uniform stress distribution associated with the 2-D model. The crack was modeled similar to the 2-D model with nodes pertaining to the crack surfaces allowed to separate. Because the 3-D model included both the exit and entry side explicitly, the actual crack length on the two sides could be included from an experimental test versus the average crack length in the 2-D FEA model. Similar experiments to Sauner and Grantt conducted by FTI included exit and entry side data and were used in this case. Because information was lacking about the shape of the crack through the thickness, a linear crack front was assumed as shown in Figure 6. The nodes to the left of the highlighted line where free to separate. Load was applied to the model and ½ the crack opening at that state is shown in Figure 6.
The 3-D FEA crack model indicated that a large portion of the crack remained closed at peak load. Opening was limited to the entry side of the crack resulting in a unique crack front shape not seen previously. The 3-D results showed that the thru thickness crack growth was significantly different than expected and alluded that the thru thickness stress distribution and was a significant factor in the fatigue crack growth of cracks from cold expanded holes.

**Experimental Determination of Crack Front Shape Thru Thickness**

The results of the past work of FTI highlighted a need to determine the shape of the crack front thru the thickness during fatigue crack growth from a cold expanded hole. The results of these types of experiments would provide a basis for validation of subsequent crack growth models while also yielding important observations of crack growth from cold expanded holes in general.

In practice, there are a large number of variables that can affect the overall fatigue life of a cold expanded hole. These include load level and part geometry. The previous 3-D FEA work suggested that the residual stress distribution thru thickness was an important part of the unusual crack growth pattern. As a result, any variable effecting the distribution thru thickness could likely affect the subsequent fatigue crack front shape during growth. One important variable that affects the stress thru the thickness is the actual thickness of the part. The residual stress at the entry and exit side are relatively unaffected by the majority of thickness ranges tested. The residual stress state between the exit and entry side regions are “stretched” as the thickness increases resulting in a decreasing percentage of the thickness being affected by the entry and exit side states as the material gets thicker.

To capture a more complete picture of the crack growth thru the thickness and the dependence of the pattern on the thru thickness distribution of the residual stress, Aluminum 7075-T651 dogbone specimens with three different thicknesses, 0.063-inch, 0.250-inch and 0.500-inch as shown in Figure 7 were fatigue tested. Some specimens of each thickness were cold expanded whereas other holes were not. All were final reamed to the same size following processing. The dogbone specimens with the geometry shown in Figure 7 were subjected to constant amplitude loading with a maximum applied stress level of 27 ksi and an R-ratio of 0.05.
Several of the specimens were cycled to failure and surface crack growth measurements were taken on the exit and entry sides of the specimen. Other specimens were cycled to a predetermined crack length and then statically broken to highlight the fatigue crack front at various surface crack lengths.

Typical surface crack growth measurements for the 0.500-inch thick specimens are shown in Figure 8. A large fatigue life improvement was observed for cold expanded specimens over non cold expanded specimens. The slower crack growth was responsible for a large part of the fatigue life benefit with cracks taking four times longer to grow from a 0.030-inch crack to a 0.200-inch crack in a cold expanded hole specimen than a non cold expanded hole specimen.
Figure 8. Surface Crack Growth Measurements from 0.500-inch Thick Specimens

The crack front pictures shown in Figures 9a and 9b for the 0.500-inch thick specimens show the evolution of the crack front. The non cold expanded hole crack growth thru the thickness was typical with an elliptically shaped crack front that grew only slightly faster thru the thickness than in the radial direction from the bore of the hole. The fatigue crack growth thru the thickness of the cold expanded hole was significantly different than the non cold expanded hole. The fatigue crack growth was arrested partway along the crack front while crack growth continued along both the bore of the hole and the entry inside surface. The result was a pronounced P shaped crack front.

A) Non Cold Expanded Crack Front Shapes

B) Cold Expanded Crack Front Shapes

Figure 9. Crack Front Shapes of Non Cold Expanded and Cold Expanded Hole 0.500-inch Thick Specimens
The crack front pictures shown in Figures 10 show the fatigue crack front just prior to final failure for 0.500-inch non cold expanded and cold expanded specimens. The fatigue cracks in non cold expanded specimens grew thru thickness prior to final failure. The cold expanded specimen fatigue cracks did not grow thru thickness prior to final failure indicating that there is a significant mechanism retarding crack growth in that direction.

Figure 10. Fatigue Crack Front Shape Prior to Failure in 0.500-inch Thick Specimens

The surface crack growth results for the 0.250-inch thick specimens are shown in Figure 11. The improvement in fatigue life observed in the 0.500-inch thick specimens was also observed in the 0.250-inch thick specimens with a period of slow, stable crack growth forming a significant portion of the fatigue life improvement. Differences were also noted in the crack growth rates and crack lengths between the exit and entry sides of the cold expanded specimens while non cold expanded specimens did not show the same difference with similar crack growth rates and lengths on both sides of the specimen.
The crack front shape pictures shown in Figures 12 showed the same P type crack growth that occurred in the 0.500-inch cracks. Unlike the 0.500-inch thick specimens, cracks in the 0.250-inch cold expanded specimens transitioned to thru thickness prior to final failure. However, the same resistance to crack growth resulting in the unusual crack shape of the 0.500-inch specimens appears to be present in the 0.250-inch specimens.

A) Non Cold Expanded Crack Front Shape

B) Cold Expanded Crack Front Shapes

Figure 11. Surface Crack Growth Measurements from 0.250-inch Thick Specimens

Figure 12. Crack Front Shapes of Non Cold Expanded and Cold Expanded Hole 0.250-inch Thick Specimens
The surface crack growth results for the 0.063-inch crack are shown in Figure 13. The crack growth in the cold expanded specimen was slower than the non cold expanded specimen as occurred in the thicker specimens. The difference in the crack growth between the exit and entry side specimens was also observed but was smaller than the thicker specimens.

Figure 13. Surface Crack Growth Measurements from 0.063-inch Thick Specimens

The crack front pictures for the 0.063-inch thick specimens are shown in Figure 14. The fatigue crack front of the non cold expanded hole appeared to transition to a thru thickness crack very early in the crack growth as expected from such a thin specimen with a nearly identical crack length on both sides. It was difficult to determine the exact shape of the crack front due to the transition from flat fracture to a 45 degree fracture surface, but it was expected that the crack front was fairly uniform with perhaps only a very limited amount of crack tunneling due to the thin material. Crack fronts from the cold expanded holes were more uniform than the 0.500-inch and 0.250-inch thick cases, but the bias to grow longer cracks on the entry side and the result was a skewed crack front towards the entry side.
3-D Finite Element Analysis of Fatigue Crack Growth from a Cold Expanded Hole

A 3-D FEA effort was initiated to study and replicate the peculiar crack front shapes that occur during fatigue crack growth from cold expanded holes in the experiments. To compare with experiments, the 0.250-inch thick specimen was modeled. As before, the mandrel and sleeve are modeled explicitly as is the mandrel pull thru process to most accurately determine the residual stress state thru the thickness. The ream is also modeled as previously by removing the corresponding elements. Crack growth is modeled by releasing displacement boundary conditions on the nodes associated with the crack front as required. A spring with a very high stiffness in compression and negligible stiffness in tension is left at the released node to simulate the crack making contact on the symmetry plane during unloading. The 3-D FEA model is shown in some detail in Figure 15.
Figure 15. 3-D FEA Crack Growth Model

The hoop stress distribution for an uncracked part before and during application of the peak load is shown in Figure 16. The thru thickness stress distribution prior to loading shows that a thin slender region of smaller compressive residual stresses occurs along the bore. A small area with a slightly lower compressive stress is present on the exit side and a larger area with a more significantly lower residual stress occurs on the entry side. When load is applied, the regions with lower compressive stresses turn to tensile with the largest tensile area again on the entry side. A large pocket of residual compressive stress remains in the interior of the part. From this loaded distribution, we can see that a crack from a cold expanded hole may begin to grow as a typical corner crack from a non cold expanded hole until it reaches the inner compressive zone. Crack growth in this region will then be slowed and would be expected to result in a crack front shape as observed in the experiments.
Figure 16. Stress Distribution with and without Applied Load and No Crack

In order to have the model grow the crack, guidelines about the direction and relative speed of crack growth from the crack front needed to be established. At this stage in the model development, the main focus was to grow the crack into the correct shape without focusing on the actual time required to do so. To minimize the complexity of the model, a simple criterion was needed that was representative of the relative speed and direction of crack growth. The crack tip opening angle (CTOA) is a fracture criteria usually used in monolithic loading to indicate the strain in front of the crack tip and measured as shown in Figure 17. In this case it served as a simple, physical representation of the amount of strain reversal at the crack tip.

Figure 17. Crack Tip Opening Angle Criteria

For cracks smaller than 0.030-inch, CTOA was measured 0.010-inch behind the crack tip. For Crack lengths longer than 0.030-inch, CTOA was measured 0.020-inch behind the crack tip. CTOA measurements were also made in the diagonal directions in the interior of the part as well. The node with the largest CTOA was identified and considered to propagate in the next step. All nodes with CTOA within 10% of the largest CTOA were
also considered to propagate. A 0.010-inch edge crack was initiated on the entry side to begin with and a 0.010-inch edge crack was added to the exit side when found to do so during the experiments based on the entry side length. In a given step, the load was applied and the CTOA values were calculated. The load was then removed and the nodes with the largest CTOA and those within 10% during the previous load step were released to simulate crack propagation. The load step was repeated. Both the CTOA on the exit and entry side cracks were watched for propagation. After some time, the FEA model was predicting cracks significantly different than the experiment and the modeling was halted. The crack evolution before this time is shown in figures 18a-k with contours indicative of the crack opening. The blue area is indicative of the un-cracked region.
Figure 18 Crack Front Evolution in 3-D FEA Crack Growth Model

Figure 19 shows the closest match between the experimental and the 2-D FEA model. The crack fronts are of similar form with slightly smaller crack growth along the bore and a larger resistance to crack growth thru the thickness observed in the 3-D FEA model than what appeared to happen in the experiment. Nonetheless, the 3-D FEA model with the simplified CTOA criteria did result in a similar crack front shape. This is promising given the simplified criteria and either a more complicated criteria or further refinements may yield even better results.
Discussion

As shown here and in numerous other studies, cracks from cold expanded holes grew significantly slower than cracks from non cold expanded holes with faster growth on the entry side of the specimen than the exit side of a cold expanded hole. The thickness appeared to affect the relative difference with thicker specimens exhibiting a larger difference in crack growth between the two sides. The relative difference could be attributed in part to the delay in growing a thru thickness crack which increased as the specimen thickness increased.

The crack front shape from the experiments showed that cracks from cold expanded holes grew different than cracks from non cold expanded holes. The distribution of the residual stress distribution thru the thickness and in the radial direction appeared to be the cause as the compressive stresses remained largest in the interior of the specimen and near the exit side surface. This resulted in an increased resistance to crack growth in these areas as indicated by the 3-D FEA crack growth results.

Together, the experimental and FEA results show that the current analytical methods require extensive modification to accurately model the crack growth properly. Current methods are based on growing cracks from cold expanded holes in the same manner as non cold expanded holes, but with a slower crack growth rate. The experimental results have shown that this type of method will not be an accurate depiction of the crack growth.

The 3-D FEA crack growth model with the simplified criteria does provide a new basis to look at crack growth from cold expanded holes. With more refinement and a more thorough look into different criteria, the actual crack front shape may replicated even
more accurately and a new methodology for predicting fatigue crack growth from cold expanded holes may be established.

Conclusions

The following are the conclusions from the work presented here:

- The 2-D approach is highly sensitive to error and is not physically representative of cracks in the tests shown here
- A new method is needed to correctly model the unique crack growth pattern from cold expanded holes
- FEA with the correct criteria is a promising tool for predicting crack growth from cold expanded holes
- As of today, experimental testing is the preferred method to determine the benefit in fatigue life and damage tolerance of cold expanded holes

Future Directions

Focus will continue on accurately predicting the growth pattern before moving to predicting rate of crack propagation. Once the crack growth pattern is properly modeled, work will begin on crack growth and fatigue life prediction methodology.

References