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Analysis of the Cold Working Process on Holes Containing Preexisting Cracks

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Cold working of fastener holes on aircraft has been proven to be an effective method to extend the fatigue service life. This process is being applied to aging aircraft that may have existing cracks at the time of cold working. The effectiveness of the cold working in the presence of several sizes of corner cracks is analytically assessed. A three-dimensional finite element analysis is performed to calculate the stresses at the crack tips with and without remotely applied load. It is found that cold working is effective to a varying degree for cracks as deep as 0.6 of the thickness.

Introduction

IN the aerospace industry, a fastener hole is considered a potential crack initiation site for structures that undergo cyclic fatigue loading because of the stress and strain concentration. However, the use of a cold expansion process (also commonly referred to as cold working) to introduce a compressive residual stress field in the material surrounding the hole can extend the service life of stressed aerospace components.[1,2]

A cold expansion technique developed by The Boeing Company and marketed by Fatigue Technology, Inc. (FTI), has been accepted as a standard practice in the United States.[3,4] Although the hole expansion technique has been in use for many years, the beneficial effect of the compressive residual stresses obtained from the expansion has not been included in the fatigue life calculation for both crack initiation and crack propagation. The major obstacle in developing analytical tools for crack prediction has been uncertainty in the quantitative assessment of residual stresses. Much of the difficulty stems from material characteristics and the three-dimensional nature of the expansion process.[5,6]

In aging aircraft, most of the fastener holes have not been cold worked when manufactured, and some of them have developed corner cracks. Some civil airlines have shown their interest in developing the cold expansion process for holes with preexisting cracks to try to extend the service life of the corresponding parts in aging aircraft.

In this paper, a three-dimensional finite element analysis of the cold expansion process is presented for two aluminum alloys, 2024-T351 and 7050-T7451, that are widely used in the aerospace industry. The three-dimensional nature of the cold expansion process is presented for both materials. Then a three-dimensional finite element analysis of the cold expansion process of holes with three different sized preexisting corner cracks is presented. A tensile stress of 124 MPa (18 ksi) is then applied to the cold-expanded precracked hole to assess the benefit of the cold expansion.

Background

Analytical investigations of residual stresses in cold-expanded holes can be divided into closed-form solutions and numerical calculations. Experimental measurement results of the residual stresses are also available; however, the available data are insufficient to facilitate the building of complex models.

In general, the analytical solutions to the cold-expanded hole problem have assumed either a two-dimensional plane stress case where uniform radial expansion of a circular hole in an infinite plate takes place, or the two-dimensional plane strain case where uniform radial expansion of an axisymmetric thick-walled cylinder takes place.[7–10] Hsu and Forman[11] obtained a solution of residual stresses around the cold-worked hole by considering the unloading of the hole after the expansion tool is removed. Subsequently, many efforts have been undertaken to extend and improve the results of Hsu and Forman for different cases. Some examples of these refined models are Rich and Impellizzeri's[12] consideration of the compressive yield during the unloading step and Chen's[13] and Zhu and Zha's[14] consideration of the Bauschinger effect. A recent solution by Wang[15] takes into account Bauschinger effect for the plane strain case. Additionally, Guo[16] extended the Hsu and Forman solution to include the effect of finite size under the plane stress case. The solutions obtained in Refs. 15 and 16 have been implemented in computer software[17] to calculate residual stresses in expanded hole problems. Controversies frequently appear in the literature because the different closed-form solutions do not agree quantitatively with experimental measuring results on residual stresses. However, many of the closed-form solutions have overlooked the reaming operation in the cold-work process.

With the rapid developments in finite element methods (FEM) and computer technology, numerical calculations can be carried out more efficiently and effectively for the cold expansion process. These developments will undoubtedly prove beneficial to the understanding of the process.

Both a two-dimensional plane stress and plane strain analysis and a two-dimensional axisymmetric analysis were conducted by Poussard et al.[5] using isotropic and kinematic plastic hardening and the von Mises yielding criterion. Contact elements were introduced to simulate the actual cold expansion process; however, there were many assumptions made about the contacting surface and boundary conditions.[6,18] Efforts were made to try to understand why cracks initiate at the surface as observed in the experiments.[19] Currently, three-dimensional calculations for fracture and fatigue life prediction of a corner crack exist, but they do not include the residual stress analysis and redistribution of the residual stresses.[17,20]

The main objective of this paper is to develop a three-dimensional FEM analysis simulating the cold expansion process of a hole with and without cracks. The three-dimensional nature of the resulting stresses in a cold expansion process without cracks will be discussed, and then the benefits of cold expansion of a hole with a corner crack will be demonstrated. Both the 7050-T7451 and 2024-T351 aluminum alloys will be analyzed for stresses developed due to cold working. Only the 7050-T7451 aluminum alloy will be analyzed with cracks.

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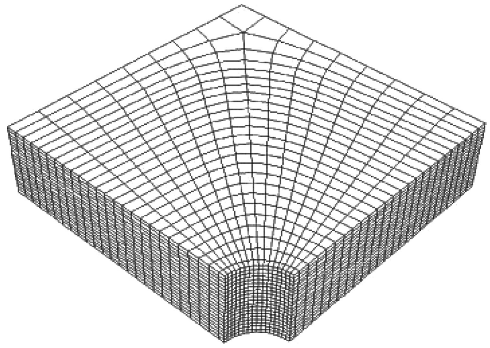
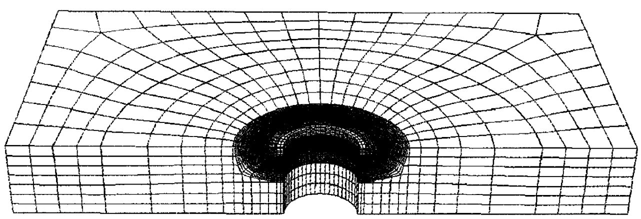
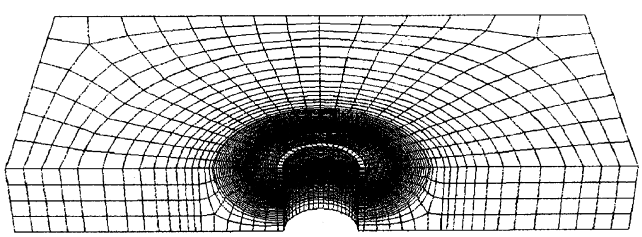


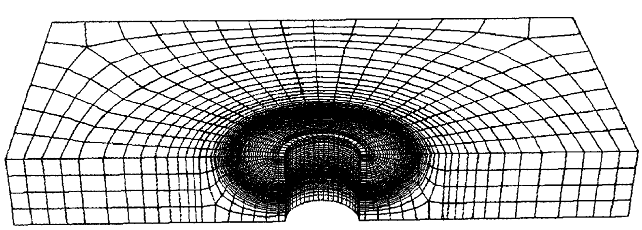
a) Cold expansion of hole without a crack



b) Cold expansion of hole with a corner crack $a/c = 1$ and $c/t = 0.2$



c) Cold expansion of hole with a corner crack $a/c = 1$ and $c/t = 0.4$



d) Cold expansion of hole with a corner crack $a/c = 1$ and $c/t = 0.6$

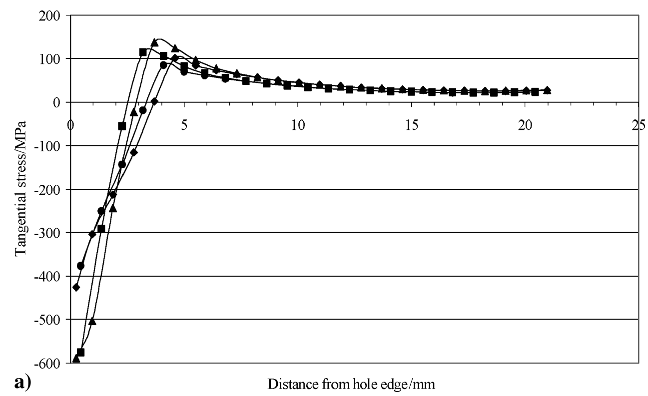
Fig. 1 Finite element mesh for a plate with cold expansion process of hole with and without a corner crack.

Analysis

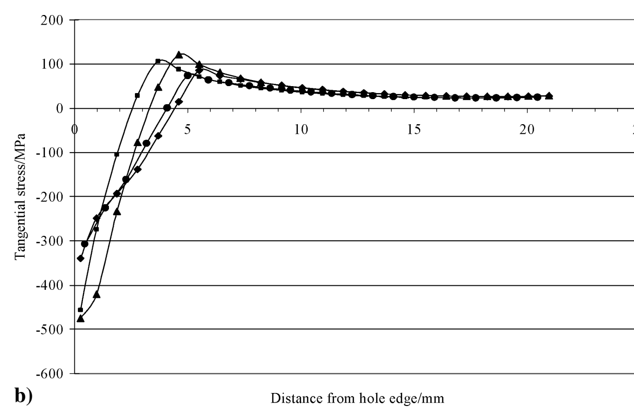
The FTI specification for the cold expansion process can be broken down into three steps germane to residual stress model development: 1) hole expansion by pulling a tapered mandrel through the hole, 2) hole recovery once the mandrel is removed, and 3) a finish ream that removes a thin layer of material around the hole.

The FTI process is representative of the most common industry practices; therefore, the three-dimensional finite element analysis developed in this paper follows the FTI specifications.

1) For hole expansion, uniform displacements are added on the nodes at the hole edge to simulate a 4% cold expansion.

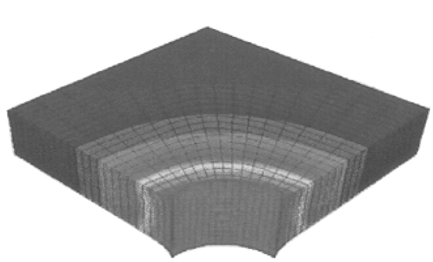


a)

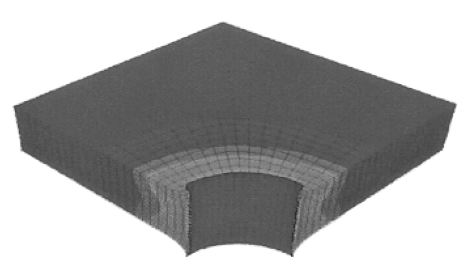


b)

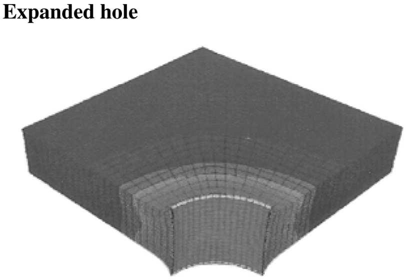
Fig. 3 Residual stress after hole released and reamed for a) 7050-T7451 and b) 2024-T351: ♦, surface, hole released; ●, surface, hole reamed; ▲, midsection, hole released; and ■, midsection, hole reamed.



a) Expanded hole



b) Released hole



c) Reamed hole

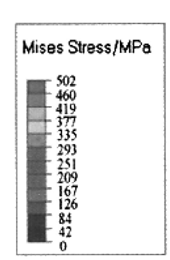


Fig. 2 Simulation of CW process in 7050-T7451.

2) For hole recovery, the removal of the mandrel and the corresponding unloading process is simulated by the removal of the boundary condition at the hole edge.

3) For finish reaming, removal of the material surrounding the hole to bring the hole to the final size is simulated by the powerful function of element removal in ABAQUS 5.8. A detailed account of this process can be found in the ABAQUS standard manual.[21] For a hole with a corner crack, the finish reaming has not been simulated because of its negligible effect on the maximum value and distribution of the residual stress.

The two materials used for the analysis, that is, 7050-T7451 and 2024-T351, are both widely used in the aerospace industry. More details of this analysis are found in Ref. 22.

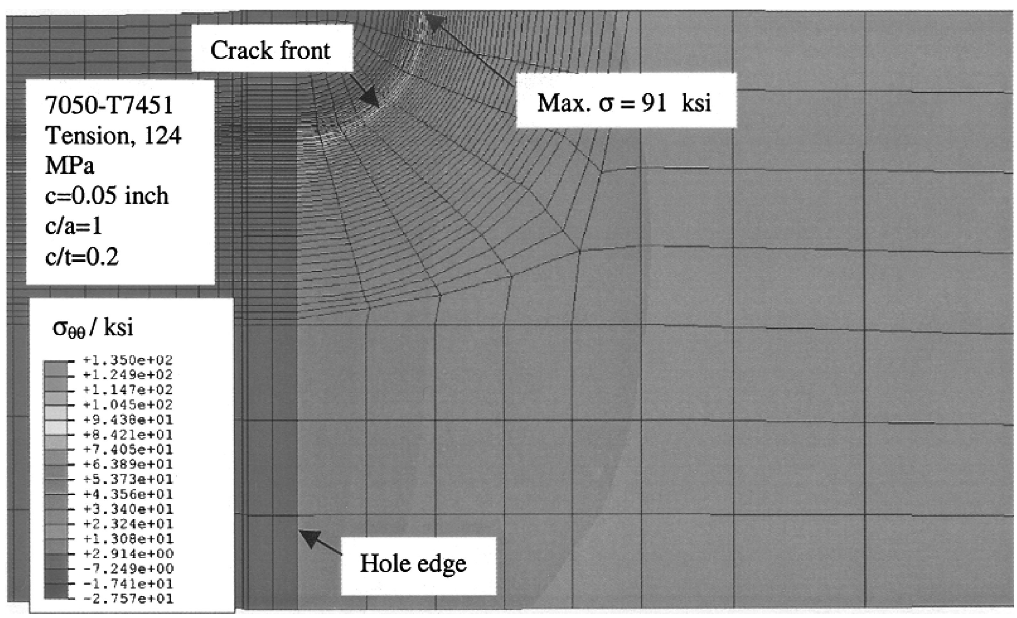
Mesh

For the cold expansion process of a hole without cracks, one-quarter of the hole is representative of the entire hole because of symmetry. The size of the model analyzed is 25.4 mm (1 in.) by 25.4 mm (1 in.) by 6.35 mm (0.25 in.) in length, width, and thickness, respectively. The initial and final hole diameter is 6.15 mm (0.242 in.) and 7.26 mm (0.282 in.), respectively. These values follow the FTI specification. The eight-node three-dimensional solid element has been adopted for the analysis. The analysis model contains 8020 elements and 9324 nodes. The mesh used is shown in Fig. 1a.

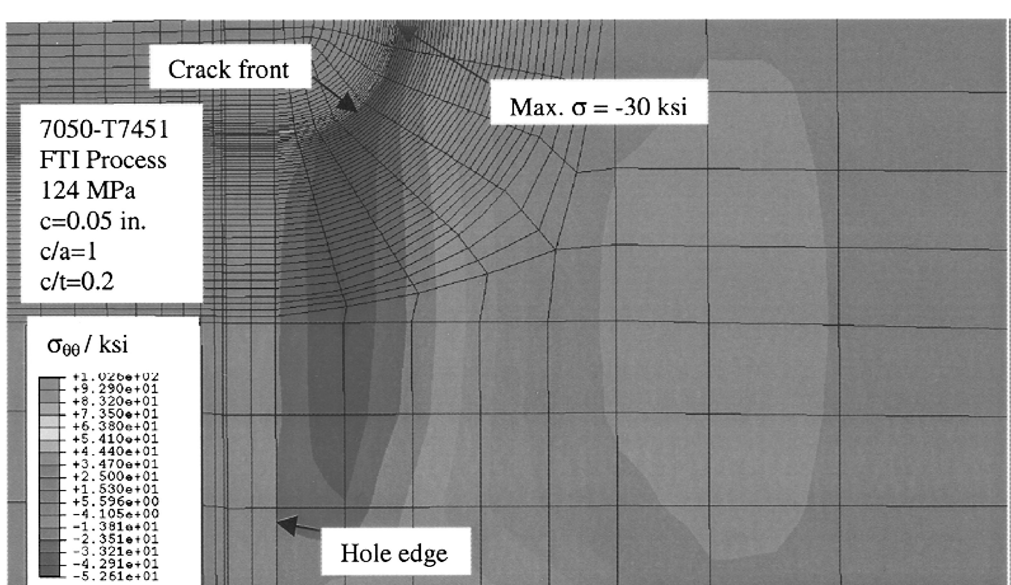
For the cold expansion process of a hole with a one-quarter corner crack, a half-symmetric model is adopted, and three different crack sizes, that is, $a/c = 1$ and $c/t = 0.2$, 0.4, and 0.6 are considered in the calculations. Here, a and c represent the crack size in the radial and thickness directions, respectively, and t is the thickness of the model. The mesh used is shown in Figs. 1b–1d. The 20-node three-dimensional solid element is used for the analysis.

Material Data

For 7050-T7451 and 2024-T351, the elastic modulus E is 71.8 GPa (10,300 ksi) and $E = 73.2$ GPa (10,500 ksi), respectively. The Poisson ratio $\nu = 0.33$. Linear plastic hardening and power plastic hardening are considered for both materials. The



a) Cracked non-CW hole with an applied remote tensile stress of 124 MPa



b) Cracked CW hole with an applied remote tensile stress of 124 MPa

Fig. 4 Tangential stresses distribution in the vicinity of the crack tip for crack size $a/c = 1$ and $c/t = 0.2$.

uniaxial proportional limit for each material is approximately 450 and 315 MPa, respectively. Both materials harden in the plastic range. The stress–strain curves for 7050-T7451 and 2024-T351 can be found in Ref. 22.

Results and Discussion

Three-Dimensional Nature in Cold Expansion Process

A typical development of plastic deformation in terms of von Mises stresses in 7050-T7451 is shown in Fig. 2. The plastic deformation is given after each of the three process steps: expansion, release, and reaming. Because the compressive tangential residual stress is responsible for the enhancement of fatigue life, only results of tangential residual stress are shown later, even though residual stresses in all three directions have been calculated.

As shown in Fig. 3, significant differences between the two materials examined are revealed for both the maximum values and distribution of the residual stresses at the surface and midsection. For the same cold-working process, the 7050-T7451 material is shown to achieve significantly higher levels of residual compressive stress. For comparison purposes, the ratio of residual stress to yielding stress of the materials is introduced. The maximum stresses are located at the edge of the hole for the different sections. This ratio is shown to be around 1.0 at the surface and 1.3 at the midsection.

In light of the residual stresses that our model shows at the different sections, it is not difficult to understand the experimental phenomenon of crack initiation sites preferring the surface of the cold-worked hole.[19] The predicted surface stresses compared well with experimental data found in Ref. 23 for 7050 aluminum. For more details, refer to Ref. 22.

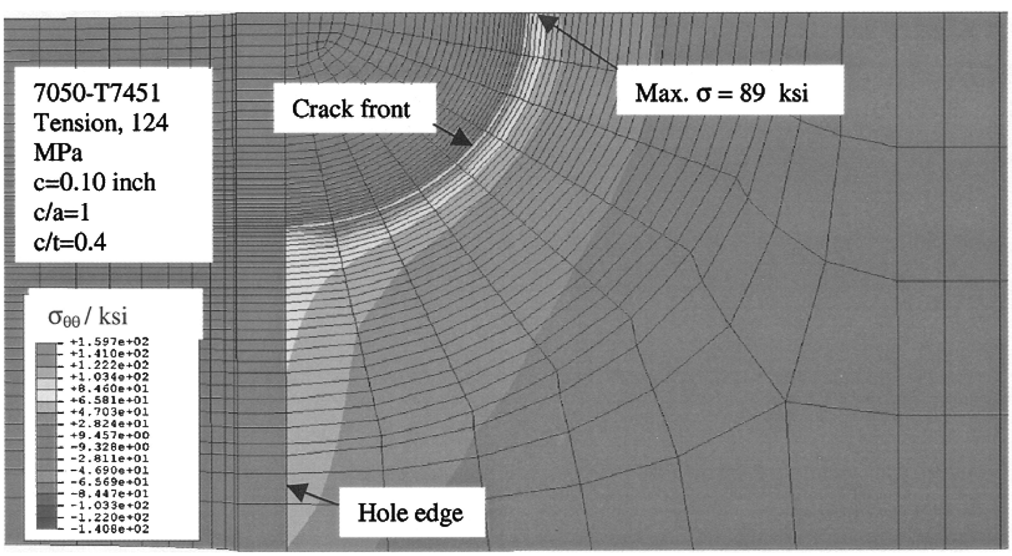
Three-Dimensional Analysis of Cold Expansion of Hole with Corner Crack

As indicated before, three are studied here with different one-quarter crack sizes, that is, $c/t = 0.2$, 0.4, and 0.6.

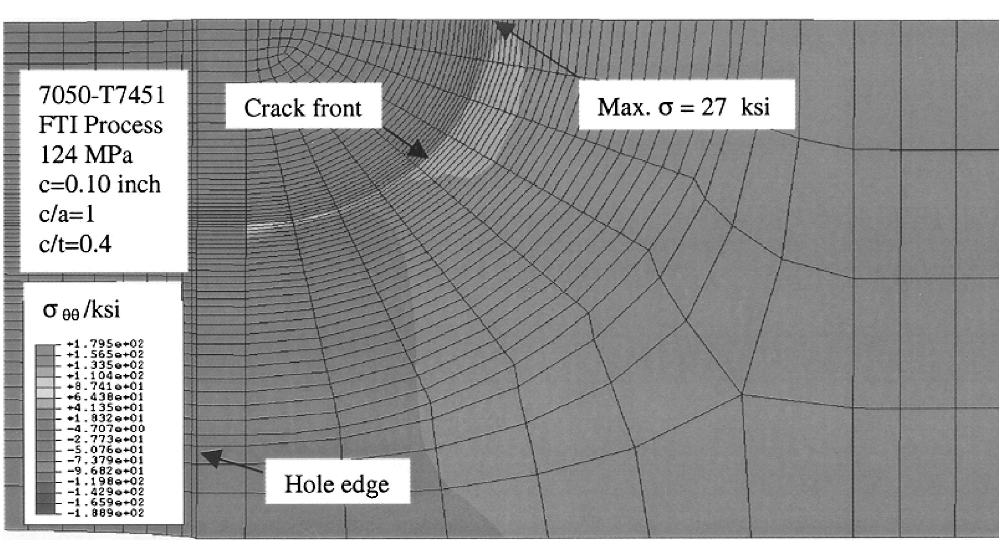
The analysis was conducted in three steps: 1) cracked body under tension, 2) cold working with corner crack, and 3) cold working with corner crack, then applying a tensile loading of 124 MPa.

The combination of steps 2 and 3 represent the cold expansion of a hole with a one-quarter crack and is compared to step 1, which represents a cracked hole without cold expansion.

The tangential stress field in the vicinity of crack tip is plotted in Figs. 4–6 for the 124 MPa applied to the unexpanded and the expanded holes (labeled FTI Process in Figs. 4b, 5b, and 6b). The stress at the crack tip in both the radial and thickness directions for all of the cases studied is tensile due to the remote tensile loading of 124 MPa. In the case of the remote applied stress to the non-cold-worked holes, the crack tip stresses are mostly at the plastic limit.

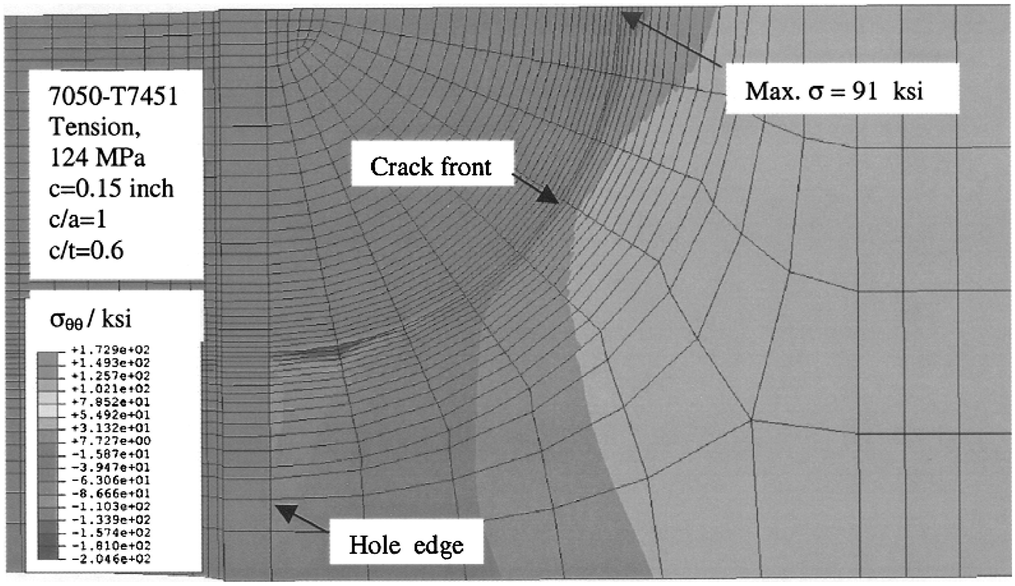


a) Cracked non-CW hole with an applied remote tensile stress of 124 MPa

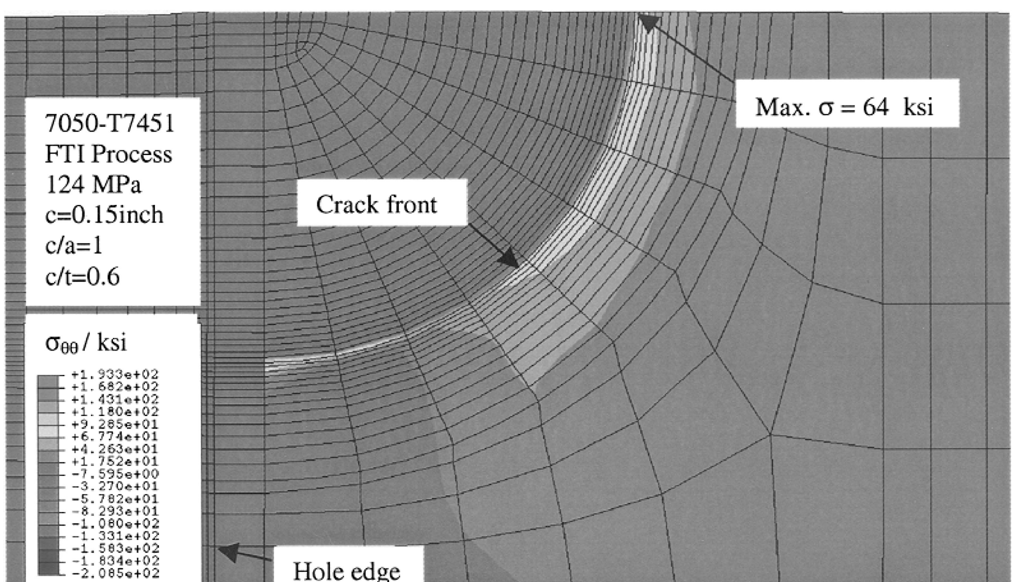


b) Cracked CW hole with an applied remote tensile stress of 124 MPa

Fig. 5 Tangential stresses distribution in the vicinity of the crack tip for crack size $a/c = 1$ and $c/t = 0.4$.



a) Cracked non-CW hole with an applied remote tensile stress of 124 MPa



b) Cracked CW hole with an applied remote tensile stress of 124 MPa

Fig. 6 Tangential stresses in the vicinity of the crack tip for crack size $a/c = 1$ and $c/t = 0.6$.

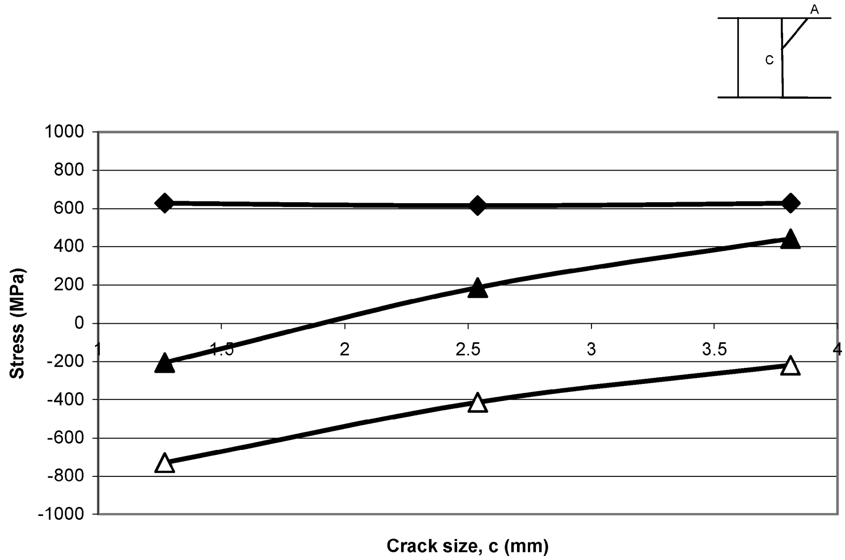
When no remote tensile loading is applied, for the holes with a corner crack of sizes $a/c = 1$, $c/t = 0.2$, 0.4, and 0.6, crack tip stresses are compressive in both the radial and thickness directions after cold expansion. That means the cold expansion was effective.

Note from Figs. 4–6 that once we applied a remote tensile loading of 124 MPa after cold expansion of the hole with a crack the stresses at the crack tips changed.

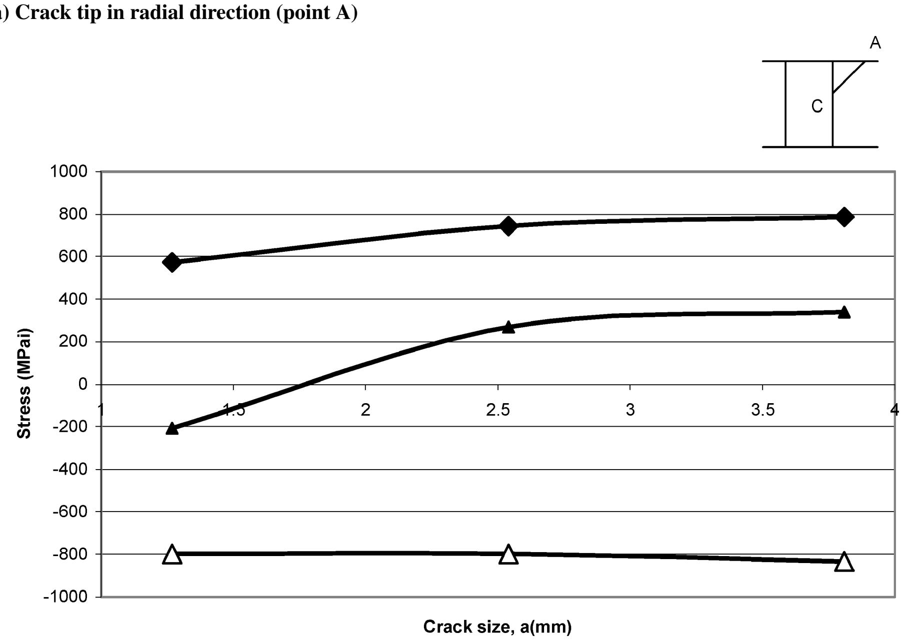
The values of stress at the crack tip in the radial and thickness directions are summarized in Fig. 7 for all cases studied. The lines labeled Tension represent the stresses present at a cracked hole not cold worked (CW) under a tensile applied remote stress of 124 MPa. The lines labeled CW with crack represent the stresses present in a CW cracked hole with no applied stress. The lines labeled CW + 124 MPa represent the stresses present in a CW cracked hole with a tensile applied remote stress of 124 MPa. In the thickness direction, the stress at the crack tip stays compressive until crack size c approaches approximately 1.8 mm, as shown in Fig. 7b. Hence, for crack sizes below 1.8 mm, there should be no further growth. For crack size c over 1.8 mm, stress at the crack tip is still significantly lower than that of a hole without cold expansion. That means the crack growth rate should be lower due to the cold working. Thus, it is believed that cold expansion is always beneficial to retard crack growth in the thickness direction.

There is a different scenario in the radial direction (Fig. 7a). Stress at the crack tip is compressive after cold expansion for the range of crack sizes analyzed; however, the value of compressive stress decreases with increasing crack size. Once the remote tensile loading of 124 MPa is applied, stress at the crack tip becomes tensile with a lower value than that of a hole without cold expansion. However, at the largest crack size analyzed (3.7 mm), the benefit of cold working is less than 200 MPa. Thus, for cracks much larger than 3.7 mm, there may be an insignificant benefit.

We examined the stress variation on the other side of the hole opposite of the crack during the different steps. Because the stress status at the surface is crucial to fatigue crack initiation, the tangential stress at the surface edge of the hole opposite the crack is given in Table 1 for the different crack sizes.



a) Crack tip in radial direction (point A)



b) Crack tip in thickness direction (point C)

Fig. 7 Comparisons of the tangential stress component at the crack tips: ♦, tension; △, CW with crack; and ▲, CW + 124 MPa.

Table 1 Tangential surface stress variations at edge of hole opposite crack

Crack size, mm	Loading status	$\sigma_{\theta\theta}$, MPa
0	CW	−376
1.27	Tension	336
1.27	CW	−403
1.27	CW + tension	−64
2.54	Tension	302
2.54	CW	−387
2.54	CW + tension	−81
3.81	Tension	327
3.81	CW	−419
3.81	CW + tension	−87

From Table 1, note that there is no significant difference in the surface stresses for cold expansion of hole with or without cracks. That means the effect of crack size on the surface stresses on the other side of the hole is slight. Moreover, the surface stresses stay slightly compressive even after we apply the 124-MPa remote tensile loading. Remember that the crack tip stress in the radial direction is compressive up to a crack length of 1.8 mm (Fig. 7a). For cracks shorter than 1.8 mm in a CW hole, there is a good chance that a new crack may initiate on the uncracked side before the small crack already present grows.

Conclusions

1) A three-dimensional finite element analysis has been developed to model the fastener hole cold expansion process in two aluminum alloys, 2024-T351 and 7050-T7451. For the same cold-working process, the 7050-T7451 alloy is shown to achieve approximately 20% higher levels of residual compressive stress.

2) The results reveal that a three-dimensional nature exists in the CW residual stress field around the hole. The residual stresses are about 30% greater in compression in the midsection than at the surface.

3) Cold expansion of holes in the 7050-T7451 alloy with a single corner crack provides beneficial stresses in all cases analyzed herein, with crack sizes $a/c = 1$ and c/t up to 0.6. However, the benefit of cold working in the presence of a preexisting crack was different for the crack tip in the thickness direction than in the radial direction.

a) In the thickness direction, a crack less than 1.8 mm in length had compressive stresses at the crack tip even with an applied remote tensile stress of 124 MPa. Those cracks over 1.8 mm in length had a stress levels of at least 400 MPa lower than the non-CW holes.

Therefore, in the thickness direction, there was always a significant benefit due to cold working.

b) In the radial direction, the benefit decreases with increasing crack size. Cracks below 2.0 mm in length still have compressive stresses at the crack tip for an applied tensile stress of 124 MPa. Therefore, cracks below 2.0 mm in length will receive the most benefit of the cold working. For cracks much larger than 3.8 mm, there may be no cold working benefit at all.

References

[1] Hertzberg, R. W., *Deformation and Fracture Mechanics of Engineering Materials*, 4th ed., Wiley, New York, 1993, pp. 578–581.

[2] Suresh, S., *Fatigue of Materials*, 2nd ed., Cambridge Univ. Press, Cambridge, England, U.K., 1983.

[3] *FTI Extending Fatigue Life of Metal Structures Materials Testing*, Fatigue Technology, Inc., Seattle, WA, 1991.

[4] "Cold Expansion to Size of Holes, Mandrel and Split-Sleeve Method," Process Specification STP52-720, Rev. A., Lockheed Aeronautical System Co., Marrieta, GA, 1992.

[5] Poussard, C., Pavier, M. J., and Smith, D. J., "Analytical and Finite Element Predictions of Residual Stresses in Cold Worked Fastener Holes," *Journal of Strain Analysis*, Vol. 30, No. 4, 1995, pp. 291–304.

[6] Forgues, S. A., Bernard, M., and Bui-Quoc, T., "3-D Axisymmetric Numerical Analysis and Experimental Study of the Fastener Hole Cold Working Process," *Computer Methods and Experimental Measurements for Surface Treatment Effects*, edited by M. H. Aliabadi and C. A. Brehhia, Computational Mechanics Publications, Southampton, U.K., 1993, pp. 61–70.

[7] Ball, D. L. "Elastic–Plastic Stress Analysis of Cold Expanded Fastener Holes," *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 18, No. 1, 1995, pp. 47–63.

[8] Nadai, A., *Theory of Flow and Fracture of Solids*, McGraw–Hill, New York, 1950, pp. 458–471.

[9] Hill, R., *The Mathematical Theory of Plasticity*, Oxford Univ. Press, Oxford, England, U.K., 1950, pp. 106–114.

[10] Hoffman, O., and Sachs, G., *Introduction to the Theory of Plasticity for Engineers*, McGraw–Hill, New York, 1953, pp. 80–95.

[11] Hsu, Y. C., and Forman, R. G., "Elastic Plastic Analysis of an Infinite Sheet Having a Circular Hole Under Pressure," *Journal of Applied Mechanics*, Vol. 42, No. 2, 1975, pp. 347–352.

[12] Rich, D. L., and Impellizzeri, L. F., "Fatigue Analysis of Cold-Worked and Interference Fit Fastener Holes," *Cyclic Stress-Strain and Plastic Deformation Aspects of Fatigue Crack Growth*, American Society of Testing and Materials, ASTM Special Technical Publications 637, Philadelphia, 1975, pp. 153–175.

[13] Chen, P. C. T., "A New Method of Predicting Residual Stresses in Autofrettaged Gun Barrels," U.S. Army Armament Research and Development Center, Rept. ARCCB-TR-86012, Watervliet, NY, 1986.

[14] Zhu, W.-X., and Zha, Z.-C., "An Elastic–Plastic Analysis of Autofrettaged Thick-Walled Cylinders," *Acta Mechanica Sinica*, Vol. 19, No. 3, 1987, pp. 245–255.

[15] Wang, G. S., "An Elastic–Plastic Solution for a Normally Loaded Center Hole in a Finite Element Circular Body," *International Journal of Pressure Vessel and Piping*, Vol. 33, No. 4, 1988, pp. 269–284.

[16] Guo, W., "Elastic–Plastic Analysis of a Finite Sheet with a Cold Worked Hole," *Engineering Fracture Mechanics*, Vol. 46, No. 3, 1993, pp. 465–472.

[17] Ball, D. L., "Stress Intensity Factor Solution Development for Interference Fit and Expanded Holes," *1999 U.S. Air Force Aircraft Structural Integrity Program Conference*, Dec. 1999.

[18] Pavier, M. J., Poussard, C. G. C., and Smith, D. J., "A Finite Element Simulation of the Cold Working Process for Fastener Holes," *Journal of Strain Analysis*, Vol. 32, No. 4, 1997, pp. 287–300.

[19] Malcon, W., Ozelton, A. T., and Coyle, G., "Fatigue Life Improvement by Cold Working Fastener Holes in 7050 Aluminum," *Fatigue in Mechanically Fastener Composite and Metallic Joints*, edited by J. M. Potter, American Society of Testing and Materials, ASTM Special Technical Publications 927, Philadelphia, 1986, pp. 53–71.

[20] Lin, X. B., and Smith, R. A., "Stress Intensity Factor for Corner Crack Emanating from Fastener Holes Under Tension," *Engineering Fracture Mechanics*, Vol. 62, No. 6, 1999, pp. 535–553.

[21] "ABAQUS User's Manual," Ver. 5.8, Hibbit, Karlson, and Sorenson, Inc., Providence, RI, 1995.

[22] Kang, J., Johnson, W. S., and Clark, D., "Three Dimensional Finite Element Analysis of the Cold Expansion of Fastener Holes in Two Aluminum Alloys," *Journal of Engineering Materials and Technology*, Vol. 124, No. 2, 2002, pp. 140–145.

[23] Ozdemir, A. T., Wang, D. Q., and Edwards, L., "Measurement of the 3D Residual Stress Distribution at Split Sleeve Cold Expanded Holes," *Proceedings of ICRS-4*, Society for Experimental Mechanics, Bethel, CT, 1994, pp. 1144–1149.