turbines, the value of C_c is positive due to a significant component of lift that increases with α in the chordwise direction. For symmetrical airfoils, the values of C_c are negative in the poststall region III. The range of incidence for which the values of C_c are negative in this region increases with the increase in the thickness ratio of the airfoil. In region IV the values of C_c are positive again. In this region, the chordwise componenets of aerodynamic forces are dominated by the suction around the leading edge. The Wortmann FX63-137 airfoil data[6] show much larger values of C_c, which are positive in regions II, III, and IV. The C_c vs α curve for a symmetrical airfoil has a direct implication in the design of a Wells air turbine for self-starting characteristics.[7,8] When such as turbine starts from rest, there is sufficient torque to start the turbine rotating due to the fact that at $\alpha = 90$ deg, C_c is positive. As the turbine speed increases, α decreases. In order to move into the operational regime (region II), the turbine has to go through a region of negative torques (region III), which results in a turbine speed much lower than the operational speed. This phenomenon, known as crawling,[8] can be eliminated by increasing turbine solidity, which effectively results in a positive value of C_c in region III.

References

[1]Jacobs, E. N. and Abbot, I. H., "Aerofoil Section Data Obtained in the NACA Variable Density Tunnel," NACA TR 669, 1939.

[2]Jacobs, E. N. and Sherman, A., "Airfoil Section Characteristics Affected by Variation of Reynolds Number," NACA Rept. 586, 1937.

[3]Blackwell, B. F. and Sheldahl, R. E., "Aerodynamic Characteristics of Four Symmetrical Aerofoil Sections Through 180 deg Angle of Attack at Low Reynolds Number," Sandia Labs., Albuquerque, NM, Rept. 87115, 1976.

[4]Beans, E. W. and Jakubowski, G. S., "Method for Estimating the Aerodynamic Coefficients fo Wind Turbine Blades at High Angle of Attack," *AIAA Journal*, Vol. 7, June 1983, pp. 747–749.

[5]Muller, T. J. and Jansen, B. J., "Aerodynamic Measurements at Low Reynolds Numbers," AIAA Paper 82-0598, 1982.

[6]Muller, T. J., "Low Reynolds Number Vehicles," AGARD-AG-288, 1985, pp. 1–69.

[7]Raghunathan, S. and Tan, C. P., "Performance of the Wells Turbine at Starting," *Journal of Energy*, Vol. 6, 1982, pp. 430–431.

[8]Raghunathan, S. and Tan, C. P., "The Aerodynamics of Wells Turbine," *Journal of Energy*, Vol. 7, 1983, pp. 226–230.

Technical Comment

Comment on "Residual Stresses in 2024-T81 Aluminum Using Caustics and Moiré Interferometry"

Michael A. Landy*
Fatigue Technology, Inc.
Seattle, Washington

IN Ref. 1, Leftheris and Schwarz discuss, among other topics, use of the split-sleeve cold-working process to produce residual strains in 2024-T81 aluminum. The widely used process, unexplained in the Note, involves the creation of residual compressive stresses by drawing an oversized mandrel through a hole using a prelubricated stainless steel split sleeve. The sleeve protects the hole wall from damage, insures that the axial motion of the mandrel is translated efficiently into force in the radial direction, and minimizes the force required to accomplish the operation. Typically, fatigue or crack-growth life improvements of 3:1, minimum, have been reported (Refs. 2 – 20, and others).

Leftheris and Schwarz split-sleeve cold-worked holes in 4 in. × 4 in. × 0.125 in. 2024-T81 plates, and then used moiré interferometry to show the distribution of residual strains (Figs. 4 and 5, Ref. 1). They note in the text that at the location where the split in the sleeve was located, the residual tangential strains are "very low." Figures 4 and 5, however, show the residual tangential strain in the location at the sleeve-split to be the highest of any circumferential location. This is shown for both the specimen cold-worked with the sleeve-split aligned with the rolling direction L and the specimen expanded with the sleeve-split aligned 90 deg to the rolling direction L-T. The lowest residual tangential strain is shown at the location corresponding to the side of the hole opposite from the split.

Received Sept. 30, 1987; revision received Nov. 4, 1987.

*Engineering Manager. Member AIAA.

Based on the above observations, Leftheris and Schwarz conclude that

1) There is "an area sector spreading radially out from the sleeve seam, where the strains are near zero after cold work," and

2) "If a crack grows where the sleeve seam is positioned, fatigue enhancement may not occur from the cold work process."

These conclusions are unsubstantiated and contradictory to in-service experience and to the results of many other comprehensive fatigue and crack-growth investigations (Refs. 2 – 20) of split-sleeve cold-worked holes in various aluminums, titaniums, and steels under constant amplitude and broadband spectrum loading conditions.

Leftheris and Schwarz's data do show that for the specimen geometry tested, higher tangential residual strains were associated with longer crack-growth lives. Their contention, however, that zero residual strain is associated with no life improvement is misleading. Residual compressive *stresses* that, in general, determine life improvement associated with a cold-working process (assuming some geometry, load spectrum, etc.) may exist with positive, negative, or zero residual strains. Alternatively, high positive residual strains may exist in a situation where no compressive residual stresses exist (i.e., no life improvement): A part that yields completely during the cold-working process.

In general, investigators performing cyclic tests cold-work the specimen holes with the sleeve-split at 90 deg to the direction of applied loading. If, as Leftheris and Schwarz contend, fatigue enhancement may not occur in that area due to residual strains being near zero, how do they explain that most failures initiate and grow from the area of the hole opposite the split? The fact that failures do occur away from the split is substantiated by Leftheris and Schwarz's empirical data. As noted above, those data (Figs. 4 and 5) show the tangential residual strain to be the lowest at the so-called 270 deg position, corresponding to the area of the hole opposite the split. Leftheris and Schwarz neglected to report the failure location with respect to the sleeve-split in the tests they performed on crack growth of cold-worked holes.

In fact, the effectiveness of split-sleeve cold-working in the area near the split is simply no longer in doubt. Many investigators of the process have focused on it, concluding that the split does not affect the fatigue enhancement performance of the sleeve cold-worked hole. For example, in Refs. 2–4, specific tests were performed to determine the influence of the split location on fatigue performance of the split-sleeve cold-worked hole. There were no discernible differences in life due to split location. Locations away from the split were found to be the more likely failure initiation site and, regardless of split orientation, a minimum life improvement of 3:1 was demonstrated. Further, it is estimated that there are over 20×10^6 split-sleeve cold-worked holes in aerospace service, dating back almost 20 years, with no reported failures. It is inconceivable that all of these holes were processed with the split away from the most critical area of the hole.

In conclusion, there is ample evidence that split-sleeve cold-working is effective and provides significant fatigue life improvement regardless of the position of the split. There is also evidence that fatigue enhancement due to split-sleeve cold-working is not axisymmetric with respect to the hole, with the area opposite from the split being the more likely failure location. There is no evidence, as Leftheris and Schwarz suggest, that there will be an area around the hole unaffected by the cold-working process. Any advances in the state-of-the-art of measurement of residual strains would be welcomed by the many users and investigators of residual stress-inducing processes. Before publishing any further findings, however, it is strongly recommended that Leftheris and Schwarz perform a thorough literature review. They would find their present conclusions contradicted by significant amounts of empirical and in-service data.

References

[1]Leftheris, B.P. and Schwarz, R., "Residual Stresses in 2024-T81 Aluminum Using Caustics and Moiré Interferometry," *Journal of Aircraft*, Vol. 24, July 1987, pp. 474–476.

[2]Hocker, R.G., "Split Sleeve, Cold Worked Holes in 7050-T73651 Aluminum Plate for Improved Fatigue Life," Northrop Corp., Hawthorne, CA, Rept. NOR 82-80, Aug. 1982.

[3]Wilhem, D.P., Fitzgerald, J.H., and Carter, J.P., "T-38 Damage Tolerance Assessment Program–NPN 3347–Crack Growth Test Summary Report," Northrop Corp., Hawthorne, CA, Rept. NOR 77-17, Oct. 1978.

[4]Cannon, D.F., Sinclair, J., and Sharpe, K.A., "Improving the Fatigue Performance of Bolt Holes in Railway Rails by Cold Expansion," *Fatigue Life: Analysis and Prediction, Proceedings of the International Conference and Exposition on Fatigue Corrosion Cracking, Fracture Mechanics and Failure Analysis*, edited by V.S. Goel, American Society of Metals, Metals Park, OH, 1986, pp. 353–370.

[5]Landy, M.A., Armen, H., Jr., and Eidinoff, H.L., "Enhanced Stop-Drill Repair Procedure of Cracked Structure," *Fatigue in Mechanically Fastener Composite and Metallic Joints*, edited by J.M. Potter, American Society for Testing and Materials, ASTM STP 927, Philadelphia, PA, 1986, pp. 190-220.

[6]*Fatigue Rated Fastener Systems*, edited by H.H. van der Linden, AGARD, NATO, Neuilly sur Siene, France, Rept. AGARD-R-721, Nov. 1985.

[7]Armen, H., Levy, A., and Eidinoff, H.L., "Elastic-Plastic Behavior of Coldworked Holes," *Journal of Aircraft*, Vol. 21, March 1984, pp. 192–201.

[8]Pearson-Smith, J.M. and Potter J.M., "Effects of Variations in Coldworking Repair Procedures on Flaw Growth and Structural Life," Air Force Wright Aerodynamics Lab, TR 82-3030, April 1984.

[9]Jongebreur, A.A. and de Koning, A.U., "Results of a Study of Residual Stresses and Fatigue Crack Growth in Lugs with Expanded Holes," *Proceedings of the 12th International Committee on Aeronautical Fatigue Conference*, May 1983.

[10]Schwarmann, L., "On Improving the Fatigue Strength of a Double-Shear Lap Joint," *International Journal of Fatigue*, Vol. 5, April 1983, pp. 105–111.

[11]Cassatt, G. and Tenclay, M., "A Comparison of Residual Stresses Around Fastener Holes Produced by Three Different Methods of Mechanical Overstraining," *Proceedings of the Spring Meeting*, Society for Experimental Stress Analysis, 1982.

[12]Derber, T., "Test Results: Verification of Fastener Hole Coldwork Benefits," Boeing, Wichita, KS, Doc. D500-10199-1, 1982.

[13]Kobler, H.G., Huth, H., and Schutz D., "Fatigue Life Improvement of Riveted Joints by Cold Working Precracked Fastener Holes," Fraunhofer Institut fur Betriebsfestigkeit, Darmstadt, FRG, Rept. 3913, 1979.

[14]Schijve, J., Jacobs, F.A., and Meulman, A.E., "Fight Simulation Fatigue Tests on Lugs with Holes Expanded According to the Split Sleeve Cold Work Method," National Aerospace Lab., The Netherlands, NLR TR 78131U, Sept. 1978.

[15]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*, edited by L.F. Impellizzeri, American Society for Testing Materials, Philadelphia, PA, ASTM STP 637, 1977, pp. 153–175.

[16]Impellizzeri, L.F. and Rich, D.L., "Spectrum Fatigue Crack Growth in Lugs," *Fatigue Crack Growth under Spectrum Loads*, edited by R.P. Wei and R.I. Stephens, American Society for Testing and Materials, Philadelphia, PA, ASTM STP 595, 1976, pp. 320–336.

[17]Toor, P.M., "Cracks Emanating from Precracked Coldworked Holes," *Engineering Fracture Mechanics*, Vol. 8, 1976, pp. 391–395.

[18]Chang, J.B., "Analytical Prediction of Fatigue Crack Growth at Cold-Worked Fastener Holes," *Journal of Aircraft*, Vol. 14, 1977, pp. 903–908.

[19]Phillips, J.L., "Sleeve Cold-Working Fastener Holes," AFML-TR-74-10, 1974.

[20]Tiffany, C.F., Stewart, R.P., and Moore, T.K., "Fatigue and Stress-Corrosion Test of Selected Fasteners/Hole Processes," ASD-TR-72-111, Jan. 1973.

Reply by Author to Michael A. Landy

Basil P. Leftheris*
Grumman Corporation, Bethpage, New York

The important message of our work was that the residual compressive stresses induced in a hole with a split sleeve are not uniform. The second message implied in our work was that the split sleeve induces residual stresses in two modes:

1) Expanding the sleeve from which material around the hole is forced radially outward causes tension-hoop stress and compression-radial stress. In this region, there is an obvious (seen with the naked eye) deformation on the surface (bulging).

2) In the area where the seam is, however, there is tension-hoop stress without the radial-compression stress. The result is a different deformation on the surface (depression, thinning).

Both regions result in compressive-residual stresses and, assuming *uniform thickness* and *isotropic materials*, there is fatigue life enhancement in both regions. There are, however, cases where the hole may be in a region where there is nonuniform stiffness (e.g., a hole drilled in a tube). In this case, the region of the seam may cause visible or invisible cracks as the mandrel is pulled through. Such cases may occur near weldments, near slight changes of thickness, or near the region where the seam is only under hoop tension. This occurs whenever the mandrel works like a wedge.

Another conclusion of our work was that finite-element codes used to analyze the residual stresses and strains around the hole by assuming axisymmetric conditions cannot be used for comparison with results obtained with the split-sleeve method. Such codes must include the geometry surrounding the hole, and they must model the deformation of the sleeve expansion in order to be trustworthy.

A final conclusion was that many investigators who used the split-sleeve method used specimens machined from large blocks of aluminum. Their results might have been different if they had used sheets of aluminum as received.

Received Sept. 30, 1987.

*Senior Staff Scientist, Structural Mechanics Corporate Research Center.