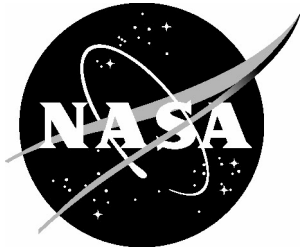


NASA/TM-2004-212658  
ARL-TR-3106



# The Effect of Hole Quality on the Fatigue Life of 2024-T3 Aluminum Alloy Sheet

*Richard A. Everett, Jr.  
U.S. Army Research Laboratory  
Vehicle Technology Directorate  
Langley Research Center, Hampton, Virginia*

---

August 2004

## The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

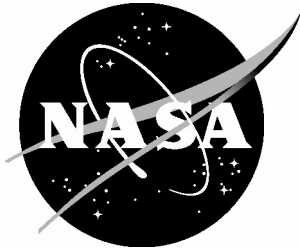
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to [help@sti.nasa.gov](mailto:help@sti.nasa.gov)
- Fax your question to the NASA STI Help Desk at (301) 621-0134
- Phone the NASA STI Help Desk at (301) 621-0390
- Write to:  
NASA STI Help Desk  
NASA Center for AeroSpace Information  
7121 Standard Drive  
Hanover, MD 21076-1320

NASA/TM-2004-212658  
ARL-TR-3106



# The Effect of Hole Quality on the Fatigue Life of 2024-T3 Aluminum Alloy Sheet

*Richard A. Everett, Jr.*  
*U.S. Army Research Laboratory*  
*Vehicle Technology Directorate*  
*Langley Research Center, Hampton, Virginia*

National Aeronautics and  
Space Administration

Langley Research Center  
Hampton, Virginia 23681-2199

August 2004

Available from:

NASA Center for AeroSpace Information (CASI)  
7121 Standard Drive  
Hanover, MD 21076-1320  
(301) 621-0390

National Technical Information Service (NTIS)  
5285 Port Royal Road  
Springfield, VA 22161-2171  
(703) 605-6000

## **Abstract**

This paper presents the results of a study whose main objective was to determine which type of fabrication process would least affect the fatigue life of an open-hole structural detail. Since the open-hole detail is often the fundamental building block for determining the stress concentration of built-up structural parts, it is important to understand any factor that can affect the fatigue life of an open hole. A test program of constant-amplitude fatigue tests was conducted on five different sets of test specimens each made using a different hole fabrication process. Three of the sets used different mechanical drilling procedures while a fourth and fifth set were mechanically drilled and then chemically polished. Two sets of specimens were also tested under spectrum loading to aid in understanding the effects of residual compressive stresses on fatigue life. Three conclusions were made from this study. One, the residual compressive stresses caused by the hole-drilling process increased the fatigue life by two to three times over specimens that were chemically polished after the holes were drilled. Second, the chemical polishing process does not appear to adversely affect the fatigue life. Third, the chemical polishing process will produce a stress-state adjacent to the hole that has insignificant machining residual stresses.

## **Introduction**

The fatigue life of metal structures is often affected by the machining process that is used in fabricating the structure (ref. 1). The machining process can increase or decrease the fatigue life. The effect of the machining process on fatigue life occurs even on the simplest of structural details, such as an open hole. An open-hole is herein defined as a hole that is drilled through the thickness of a sheet of material where a rivet would be inserted to join two sheets of a material to form a joint. Since the open-hole detail is often the fundamental building block for determining the stress concentration of built-up structural parts, it is important that any factor that can affect the fatigue life of the open hole be well known. The main objective of this work is to determine which type of fabrication process would have the least effect on the fatigue life of the open hole structural detail.

This work was initiated during the process of evaluating the load interaction effects that could possibly occur from the load sequences that are experienced by commercial transport fixed-wing aircraft. At the start of this study it was originally decided to use a drilling process that was typical of the type used in the aircraft industry. Here a pilot hole is drilled and then followed by a reamer that would bring the hole size to the desired diameter. Since it was known that hole drilling can enhance fatigue life by placing residual compressive stresses at the surface of the hole, it was decided to compare the fatigue life of holes made with a typical industry technique to a process that has been used to minimize the compressive residual stresses. If the effect on fatigue life using the industry drilling technique was significant, it would be preferred to use a drilling process that had the minimal affect on fatigue life so the affects of the loading sequence on fatigue life could be studied without the analytical complications that compressive residual stresses would impose.

Three mechanical drilling procedures were used to make the open hole test specimens. One of the mechanical procedures was typical of a procedure used in the commercial fixed-wing aircraft industry. A fourth and fifth group of test specimens were mechanically drilled and then chemically polished to remove residual-stress-affected material and tool marks. Details of these procedures will be given in another section of this paper.

## Test Program

To assess the affect on fatigue life of the fabrication procedure used to make an open hole, constant-amplitude fatigue tests at a stress ratio,  $R = -1$ , were conducted on 2024 aluminum alloy test specimens where the hole was made with several drilling techniques. Spectrum load tests were also conducted to help clarify the issue of whether chemically polishing adversely affects the fatigue life. This section describes the material, test specimen configuration, constant-amplitude and spectrum load tests, and the drilling procedures used to make the holes.

### Material and Test Specimen Configuration

The material used for this study was 2024-T3 aluminum alloy sheet taken from a stock of material at the NASA Langley Research Center which has been used for fatigue and fracture studies over several decades (ref. 2,3). The alloy 2024 has been used in the lower wing skin of many commercial transport aircraft. The material from the Langley stock has a yield strength of 52 ksi and an ultimate tensile strength of 72 ksi (ref. 3). The fatigue endurance limit for this material was shown to be approximately 8 ksi from a previous test program (ref. 4). The nominal thickness of this sheet material is 0.090 inches.

The test specimens were machined to the configuration shown in Figure 1. The center hole diameter was 0.25 inches which resulted in an elastic stress concentration factor,  $k_T$ , of 3.02 based on gross section (width=3.33 inch), or 2.79 based on net section (width=3.08 inch).

### Constant-Amplitude Tests

All constant-amplitude tests were conducted in servohydraulic, electronically- controlled test stands at a stress ratio,  $R=-1$ . The tests were run at a cyclic frequency of 10 Hz and loads were controlled within 1 percent. All fatigue lives reported herein correspond to specimen failure. The maximum stress level for all tests was 13.6 ksi based on the gross section. With a  $k_T$  of 3.02 (gross section) the stress adjacent to the hole was below the yield stress of the material. This was considered essential because yielding the material adjacent to the hole would possibly negate any residual stresses placed in the material by the hole fabrication procedure. Guide plates were used to prevent buckling under the compressive loads. The guide plates were lined with teflon sheets to reduce friction between the specimen and guides and were loosely bolted on either side of the test specimens.

### Spectrum Tests

Fatigue spectrum tests were also conducted using a test spectrum typical of fixed-wing commercial transport aircraft. To protect proprietary information in this paper the spectrum is referred to as commercial transport, type A. The loads in this spectrum are typical of those experienced on the lower wing surface. As in the constant-amplitude tests, guide plates were used to prevent buckling under compressive loadings. These tests were run in a servohydraulic, electronically-controlled test machines with loads controlled within 1 percent.

## Hole Fabrication Procedures

Test specimens were fabricated using five different procedures to make the holes. Three sets were mechanically drilled and two sets were drilled and then chemically polished. The following sections will describe these procedures.

Two drills, sanded. This fabrication procedure is similar to a procedure used in the fabrication of fixed-wing commercial transports. First, a pilot hole is drilled about 0.01 inches less than the final hole diameter with an aluminum backing plate to reduce burrs. Then a reamer is used to produce the desired hole diameter. Finally, the specimen surface is sanded around the hole using 600 grit paper. Burrs inside the hole are not removed.

Four drills, deburred. Four progressively larger drill sizes are used to obtain the desired hole size. A pilot hole is first drilled to about 0.016 inches less than the hole diameter desired. Final cuts are made removing 0.010 inches of material, then 0.004 inches, and finally 0.002 inches. The hole is then deburred on the specimen surface and inside the hole with 600 grit paper.

Multi-drills. Seven progressively larger drill sizes are used to obtain the desired hole size. For the 0.25 inch hole used in this study the drill sizes were as follows: 1/8, 5/32, 3/16, 13/64, 7/32, 0.238, and then a reamer to obtain the 0.25 inch final diameter. The hole is then deburred on the specimen surface and inside the hole with 600 grit paper.

Two drills, chemically polished. This procedure uses the same drilling technique as the two drills, sanded procedure described above, except the specimen surface is chemically polished after drilling and not sanded. The chemically polishing solution is 80% phosphoric acid, 5% nitric acid, 5% acetic acid, and 10% water, by volume (ref. 4). The solution is heated to 220° F for five minutes. The chemical polishing procedure is designed to deburr the hole as well as to remove a layer of material that might contain machining residual stresses. Specimens were submerged in the solution for five minutes.

Four drills, chemically polished. This procedure uses the same drilling technique as the four drills, deburred procedure described previously. After the hole has been mechanically drilled, the chemically polishing procedure just described is used to remove any burrs while removing a layer of material that might contain machining residual stresses. Specimens were submerged in the solution for five minutes.

## Results and Discussion

Either eight or ten constant-amplitude fatigue tests were conducted for each type of hole preparation. Each set was conducted at  $R=-1$  and a maximum stress of 13.6 ksi. As previously stated, this keeps the local stress adjacent to the hole at approximately 26 % of the yield stress of the material. Hence, the stress state at the hole should be that of the combined effect of the applied loading and any residual machining stresses resulting from the hole drilling process. In the discussion that follows two major groups of test specimens are presented. The first group are tests that were done on specimens where the holes were mechanically drilled. The second major

group of specimens were chemically polished after the holes were drilled in order to deburr the holes as well as remove a layer of material that might contain machining residual stresses.

Figure 2 shows the results of the constant-amplitude fatigue tests. The trend of the test data shows that the average fatigue life of the mechanically-drilled holes is two to three times more than the chemically polished specimens. Three possible explanations for this observation are proposed. The first explanation that could be made is that the mechanically-drilled specimens had a longer average fatigue life because the drilling process left a residual compressive stress field adjacent to the hole which reduced the local stress state and enhanced the fatigue life. A second possibility is that the chemically-polished holes removed these compressive residual stresses thus decreasing the fatigue life. However, a third possible explanation would be that pits caused by the chemical-polishing procedure could act as crack initiation sites that would shorten the fatigue lives of these specimens. These three possibilities will be discussed in the following sections.

### Mechanically-Drilled Test Results

A previous cooperative test program of AGARD (Advisory Group For Aerospace Research & Development), (ref. 3), was conducted to study the growth of short-cracks in 2024-T3 aluminum alloy. One of the conclusions of this program was that mechanically- drilled holes can leave compressive residual stresses that often increase fatigue lives. The results of the tests performed in this study, and shown in Figure 2, support this conclusion. If it can be shown that chemical polishing does not adversely affect the fatigue life of 2024-T3, but merely removes the compressive residual stresses this conclusion will be further substantiated. The next section of this paper will attempt to show that the chemical-polishing procedure does not adversely affect the fatigue life of 2024-T3 aluminum alloy.

### Chemically-Polished Test Results

Three sources of test data tend to support the conclusion that the chemical polishing procedure does not adversely affect the fatigue life of 2024-T3 aluminum alloy. Previous test programs on this material have been conducted using chemically-polished specimens where scanning electron microscope examinations showed that the fatigue cracks started from metallurgical sites such as inclusion particles (ref. 3) and not from pits induced by the polishing procedure (ref. 3). Another polishing procedure that is often used on fatigue specimens is electro-polishing. A set of fatigue tests run on specimens that were electro-polished were conducted on the Langley stock of material in the late 1950's (ref. 4). The results of these tests superimposed on the tests from this current study are shown in Figure 3. Although the tests in reference 3 were conducted on test specimens that had widths of two and four inches, these widths were on either side of the current test specimen width which was 3.3 inches. A comparison of the test results in Figure 3 shows very good agreement between the electro-polished specimens and the chemically polished specimens. Further evidence of the use of electro-polishing as an approved method for fatigue specimen finishing is that this procedure has often been used on specimens whose fatigue test results are reported in the military specifications (ref. 5). The microscopic examinations from the work done in reference 2 and the favorable comparison of the electro-polishing data to the current chemically polished test data, indicate that chemically polishing does not affect the fatigue life of 2024-T3 aluminum alloy.



## Spectrum-Test Results

Another indication that chemical polishing does not adversely affect fatigue life comes from fatigue spectrum tests that were conducted as a part of this study. These tests were run using a typical commercial transport loading spectrum described previously. One pass through the load spectrum contains 208,022 cycles with an average  $R = 0.5$ . Ten tests were run on each of two groups of specimens. One group was fabricated using the 4-drill chemically polished procedure and the other group was the 2-drill sanded specimens with no chemical polishing. Test results from these tests are shown in Figure 4. The test results shown on this figure show very little difference in the average fatigue lives of the two sets of specimens (2,790,000 versus 2,460,000 cycles) indicating that the local stress states are similar for both specimen groups and that any pitting that could possibly result from the chemical polishing procedure has very little influence on fatigue life. The applied loads in these spectrum tests were high enough so that the local stresses adjacent to the hole exceeded the yield stress of the material approximately 15% of the time in 1,000,000 cycles. As stated previously, when applied loads cause the local stresses to exceed the yield stress of the material, the compressive residual stresses caused by the hole drilling procedures are negated (ref. 6).

## Conclusions

This paper presented the results of a study whose main objective was to determine which type of fabrication process would least affect the fatigue life of the open-hole structural detail. Three conclusions can be drawn from this study.

1. The machining processes used to drill holes in 2024-T3 aluminum alloy resulted in an increase in fatigue life when compared to the fatigue lives of the chemically polished specimens. Presumably this life enhancement is due to compressive residual stresses left in the specimen from the drilling process.
2. The chemical polishing technique used in this study produces similar results to other non-mechanical polishing methods and does not adversely affect the fatigue life of 2024-T3 aluminum alloy.
3. A chemical polishing technique like that use in this study appears to reduce the residual stress-state adjacent to a drilled hole.

## References

1. Wieland, D.H., Cutshall, J.T., Burnside, O.H., and Cardinal, J.W., "Analysis of Cold Worked Holes for Structural Life Extension," FAA/NASA International Symposium on Advanced Structural Integrity Methods for Airframe Durability and Damage Tolerance, NASA Conference Publication 3274, Part 2, September 1994.

2. Grover, H.J., Hyler, W.S., Kuhn, P., Landers, C.B., and Howell, F.M., "Axial-Load Fatigue Properties of 24S-T and 75S-T Aluminum Alloy as Determined in Several Laboratories," NACA TN 2928, May 1953.
3. Newman, J.C., Jr. and Edwards, P.R., "Short-Crack Growth Behavior in an Aluminum Alloy - An AGARD Cooperative Test Programme" AGARD-R-732, December 1988.
4. Landers, C.B. and Hardrath, H.F., "Results of Axial-Load Fatigue Tests on Electropolished 2024-T3 and 7075-T6 Aluminum-Alloy-Sheet Specimens with Central Holes," NACA TN 3631, March 1956.
5. Military Handbook, Metallic Materials Elements for Aerospace Vehicle Structures, MIL HDBK-5E, Vol. 1, June 1987.
6. Dowling, N.E., "Mechanical Behavior of Materials," Prentice Hall, Inc., New Jersey, 1993.

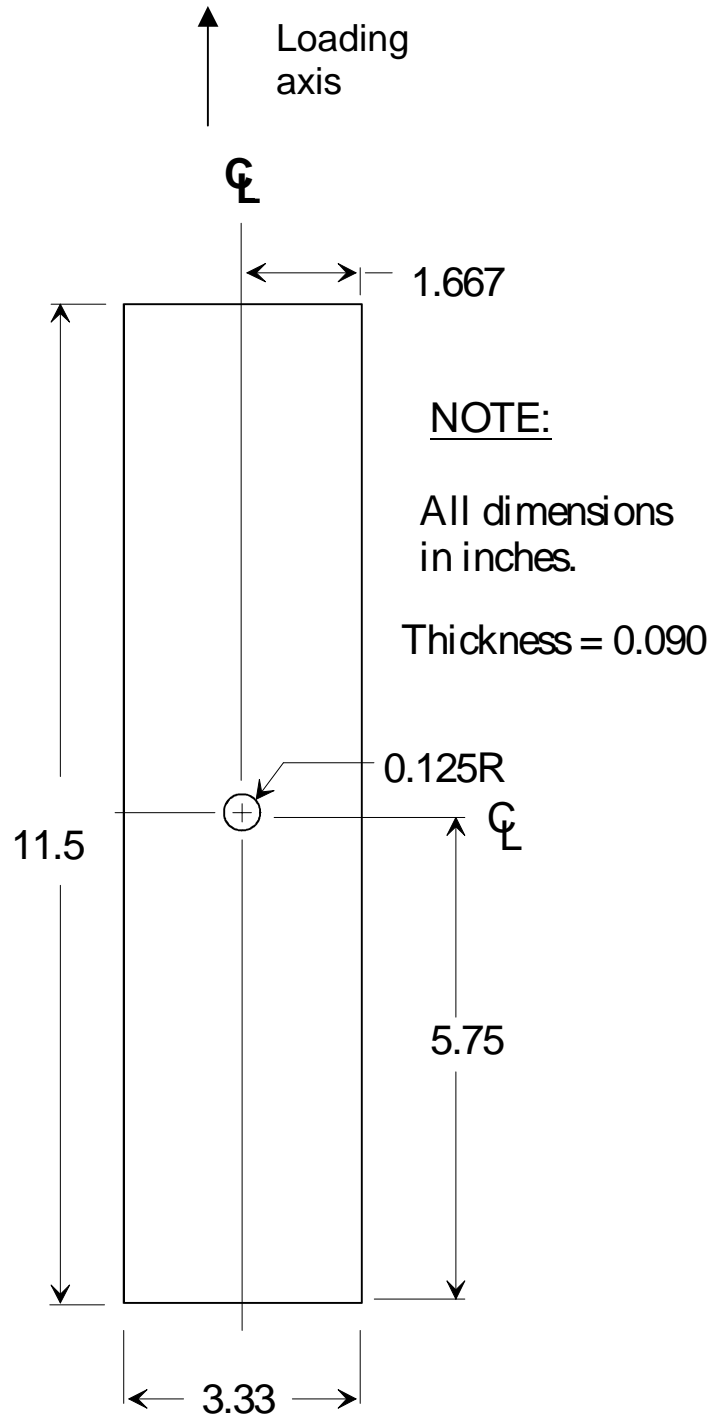


Figure 1. Test specimen geometry.

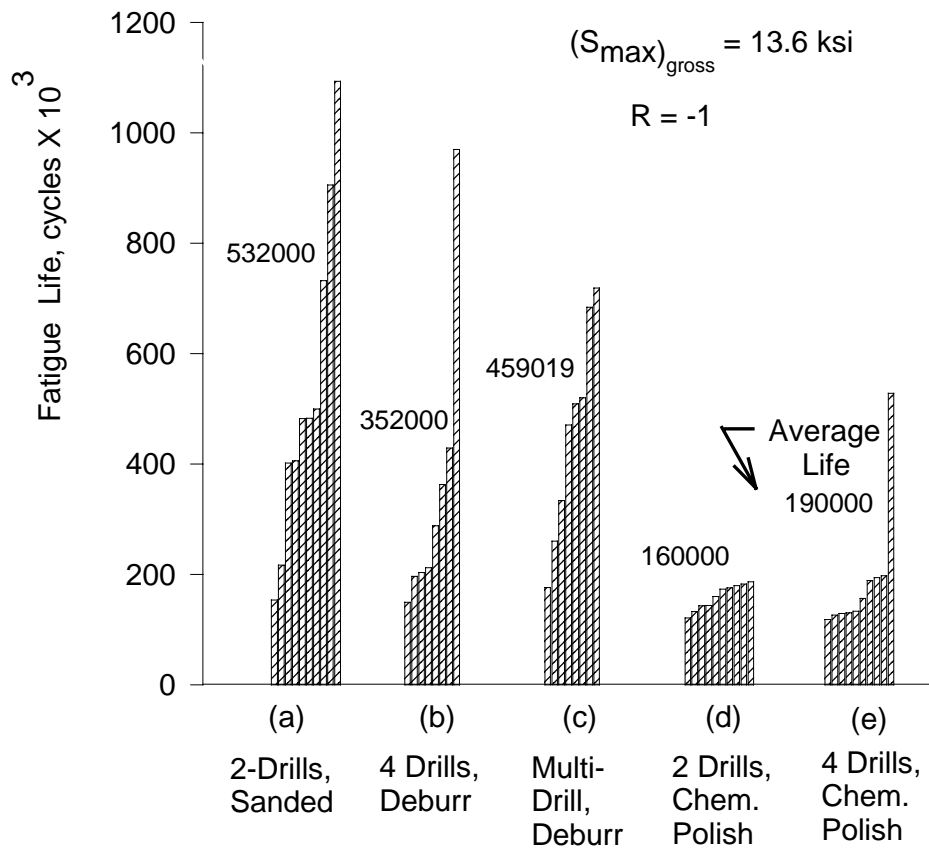


Figure 2. Effect of drilling procedure on fatigue life.

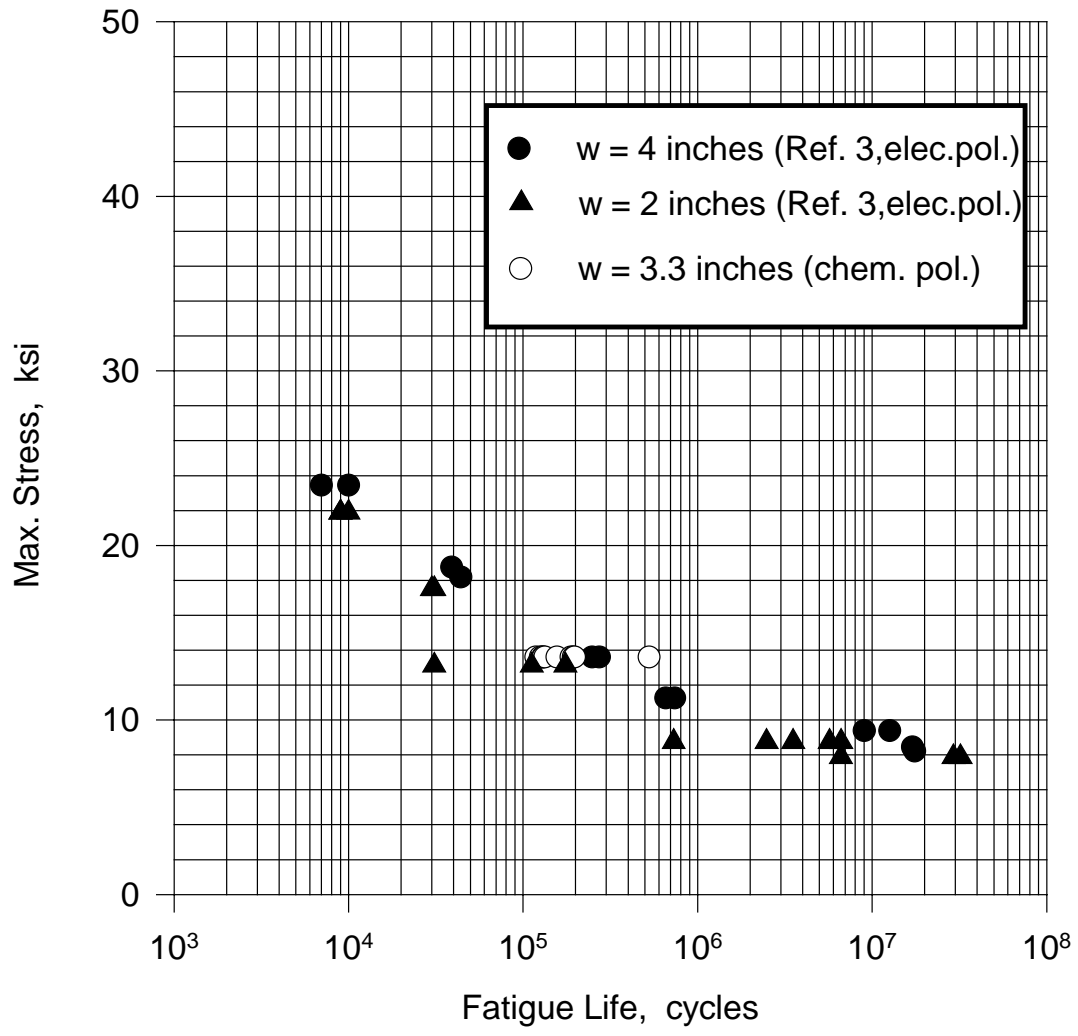


Figure 3. Comparison of electro-polishing to chemically polishing fatigue test results under R = -1 loading.

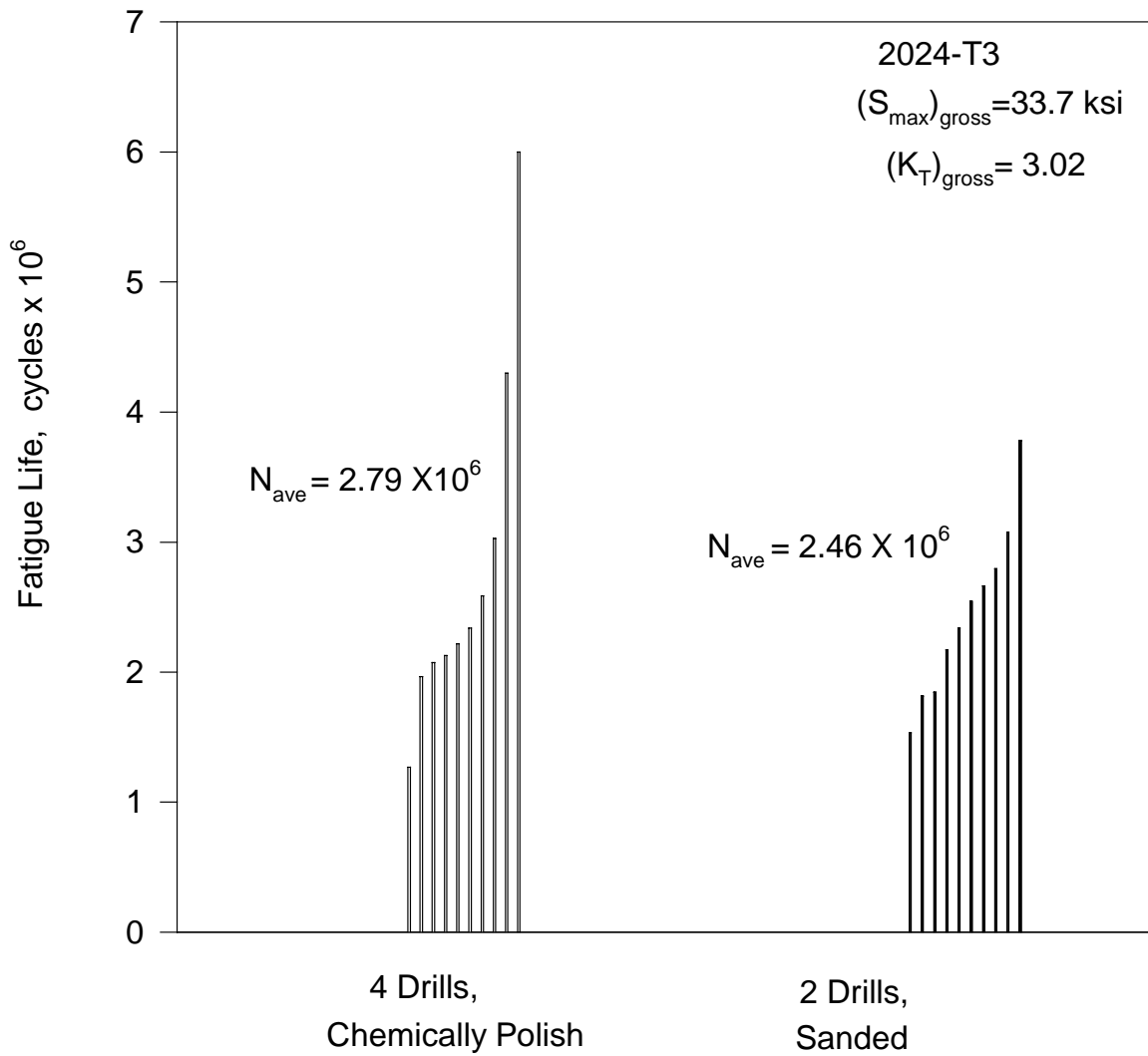


Figure. 4 Comparison of fatigue tests between chemically polished specimens and specimens without polishing under a commercial transport loading spectrum.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b></p>					
1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE		3. DATES COVERED (From - To)	
01-08-2004		Technical Memorandum			
4. TITLE AND SUBTITLE The Effect of Hole Quality on the Fatigue Life of 2024-T3 Aluminum Alloy Sheet				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Everett, Richard A., Jr.				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER 23-762-30-71	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199			8. PERFORMING ORGANIZATION REPORT NUMBER  L-19011		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001 and U.S. Army Research Laboratory Adelphi, MD 20783-1145			10. SPONSOR/MONITOR'S ACRONYM(S)  NASA		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) NASA/TM-2004-212658 ARL-TR-3106		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category 26 Availability: NASA CASI (301) 621-0390      Distribution: Standard					
13. SUPPLEMENTARY NOTES An electronic version can be found at <a href="http://techreports.larc.nasa.gov/ltrs/">http://techreports.larc.nasa.gov/ltrs/</a> or <a href="http://ntrs.nasa.gov">http://ntrs.nasa.gov</a>					
14. ABSTRACT This paper presents the results of a study whose objective was to determine which type of fabrication process would have the least affect on the fatigue life of the open hole structural detail. A test program of constant amplitude fatigue tests was conducted on five different sets of test specimens each made using a different hole fabrication procedure. Three of the sets used different mechanical drilling procedures while a fourth and fifth set were mechanically drilled and then chemically polished. Two sets of specimens were also tested under spectrum loading to aid in understanding the effects of residual compressive stresses on fatigue life. Three conclusions were made from this study. First, the residual compressive stresses caused by the hole drilling process increased fatigue life by two to three times over specimens which were chemically polished after holes were drilled. Second, the chemical polishing process does not appear to adversely affect the fatigue life. Third, the chemical polishing process will produce a stress-state adjacent to the hole that has insignificant machining residual stresses.					
15. SUBJECT TERMS Aluminum; Chemical polishing; Drilling processes; Fatigue life; Residual stresses; Stress concentration					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: <a href="mailto:help@sti.nasa.gov">help@sti.nasa.gov</a> )
U	U	U	UU	15	19b. TELEPHONE NUMBER (Include area code) (301) 621-0390