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Summary of Research:

Exploratory Investigation into the Durability of Beneficial Cold Worked Fastener Holes in Aluminum

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Submitted by

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Introduction

Cold working fastener holes in aluminum alloys is a widely used technique in the aerospace industry for improving the fatigue performance of structures. A compressive tangential stress introduced in the material during the cold working of the hole reduces the natural tendency of the material to crack at the holes under cyclic tensile loading. It is a lucrative technique for the aerospace industry in that it provides an increase in performance without any weight cost.

Background

The technique most commonly used to cold work fastener holes is a process introduced by Fatigue Technology Incorporated (FTI) of Seattle, USA in the early 1970s. It is a high interference process involving the pulling of an oversize mandrel through the hole to be cold worked. A thin lubricated sleeve is inserted between the hole and the mandrel before cold working in order to limit material flow in the direction of mandrel movement. The process calls for an optimum 4% radial expansion of the hole and subsequent mild reaming. Research has shown this cold expansion to have a marked effect, often eliminating crack growth problems in fastener holes. [1]

It is proposed that under thermal exposure or bolt bearing loads, the benefits of cold working may decay with time. Previous work has had limited scope in the study of the durability of the beneficial compressive stresses, focusing mainly on crack growth through the stress field. The purpose of this research is to address the issue of thermal exposure as it relates to supersonic flight conditions and hot runway situations as well as to address bolt bearing exposure in cold worked holes in aluminum alloys. It is also desirable to provide additional basis for which to refine and develop analytical crack growth models.

Program

Materials and Cold Working

Two common aircraft aluminum alloys are under investigation in this research. The 2024 alloy that has been in common use for some time in aircraft structures and a 7050 alloy that represents the new generation of aerospace aluminum alloy. A good deal of research has been conducted on the 2024 material, and crack growth data and damage tolerance data is available. The 7050 material is less developed in this respect, this program aims to further the knowledge base for the material. The two materials under investigation represent a spread in yield strength; we expect to find differences in the behavior of the materials and we hope to be able to draw some conclusions about the stress relaxation in higher and lower strength materials.

Lockheed of Marietta, Georgia has provided 2024-T351 and 7050-T7451 cold worked specimens for test purposes. Lockheed employs a cold working procedure based directly on the FTI specifications for a 4% cold worked hole. Dr. Newman of NASA-LaRC has also provided additional 2024 and 7050 in material form for further study.

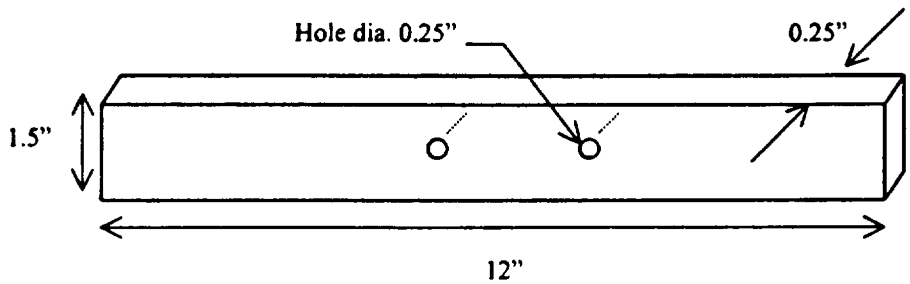

Figure 1: Specimen Geometry

Residual Stress Measurements

It is of importance to this study to have a means by which to measure the state of residual compressive stress around the hole. We have a few methods of accomplishing this at our disposal.

Analytical closed form solutions have been developed in the past to model the expansion of circular holes in material. A 1975 model developed by Y.C. Hsu and R.G. Forman [2] which assumes plane stress and a Ramburg-Osgood material for an exact stress solution around an expanded hole in an infinite sheet is being considered for comparison with experimental data. A 1977 paper by Rich and Impellizzeri developed a model which assumes plane strain in an elastic-perfectly plastic material [3], this model is also under consideration for comparisons.

Two experimental techniques that are available are being used to determine the state of stress around the holes. They are both based on lattice spacing measurement through the diffraction technique.

The first, X-ray diffraction, has been commonly used for stress measurements for decades. The angle at which an incident X-ray beam diffracts off of a subject gives a basis for determining the lattice parameter. This can be related back to residual stress. A drawback to using X-rays is that they will only penetrate the surface layer of the aluminum. The surface may or may not be representative of the internal stress state. X-rays are still a valuable tool however. X-ray measurements can be compared with other techniques for determining residual stress.

A second technique uses neutrons to accomplish the same diffraction angle measurement. Neutrons have the advantage of being capable of penetrating the aluminum and providing a through thickness average lattice parameter.

Mechanical Testing

Mechanical testing in the form of uniaxial tension-compression fatiguing of the specimens is planned as well. Mechanical testing will give crack growth data. This data will serve as another experimental basis for quantifying the stress relaxation effects in the specimens.

Progress

Specimens

Currently all specimens necessary for the test matrix to be run have been obtained from Lockheed. Specimen quality became a concern after some study of the specimens. Physical measurements on the specimens showed a good deal of variation between specimens. This apparent variation has been verified to have an effect on the cold worked hole stress field to some degree by neutron diffraction measurements. Figure 2 represents preliminary hoop strain measurements around the cold worked hole for a selected set of 7050 specimens.

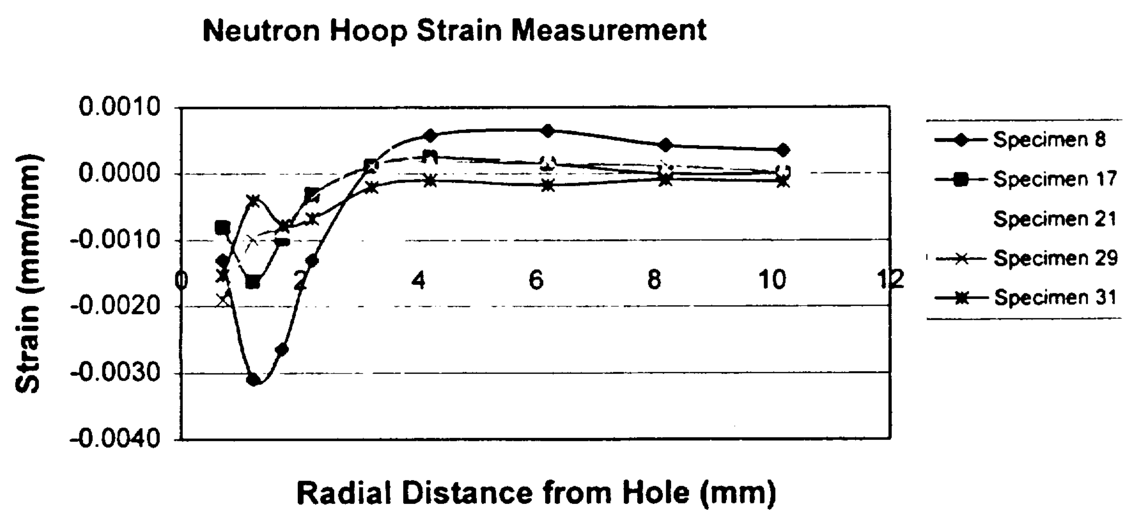

Figure 2: ORNL Strain Data for Specimens with Cold Worked Holes

As can be seen in Figure 2, a significant amount of variation exists between specimens. This type of variation will make comparisons between specimens difficult. It is suggested that this variation is due to the manufacturing techniques used to manufacture the specimens. Discussion with Lockheed has revealed that post-cold work reaming of the holes was performed by hand drill. Marks left in the bore of the cold worked holes suggests that the reaming tool may not have been sharp or that the hand technique used to perform the reaming may have caused irregularities. This type of variation very likely exists in manufacturing practices at Lockheed and other manufacturers, however this study has not been designed to encompass manufacturing statistics.

Residual Stress Measurements

Oak Ridge National Laboratory (ORNL) in Tennessee has a neutron residual stress facility that is available for our use through the Oak Ridge Associated Universities program. Two trips to the ORNL High Flux Isotope Reactor (HFIR) have been made for preliminary measurement purposes. The initial set of measurements provided us with some experience in how to handle the specimens to perform the test and of a material problem issue. The large grain size of the 2024 material caused the statistical results of the strain measurements to be unacceptable. The 7050 material proved to be much more suited to measurements because of the significantly smaller grain size.

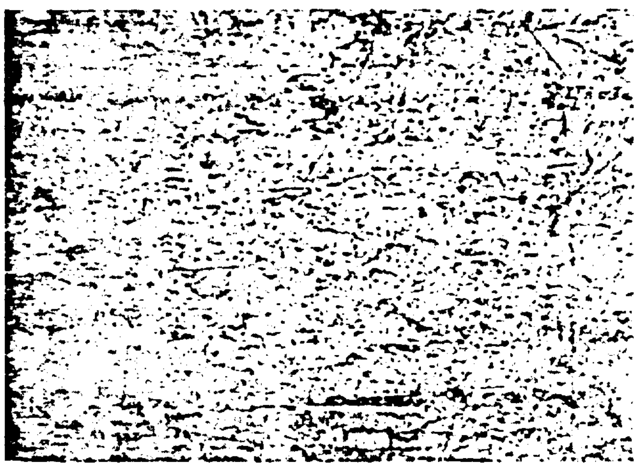

Figure 3a: 2024 Aluminum alloy

Average grain Size: 585 μm in rolling direction, 260 μm in direction perpendicular to rolling.

Figure 3b: 7050 Aluminum alloy

Average grain size: 42 μm dominantly isotropic.

A second visit to the ORNL HFIR was more successful at obtaining the stress field. We were able to obtain hoop strain measurements for five 7050 specimens, this data was presented in the Figure 2.

In order to verify the neutron technique, we have considered X-ray diffraction for comparisons. An X-ray facility is being set up at ORNL now, however it will not be operable for approximately another month. TEC of Knoxville was contracted to perform X-ray residual stress measurements included in this report. These measurements were performed on a single 7050 specimen that was also examined at the ORNL HFIR neutron diffraction facility.

At this point, a complete strain tensor has not been determined through neutron diffraction and direct comparison can only be accomplished through approximations. Figure 4 was created assuming that there is no contribution to the hoop stress from the other two components of stress at the point of measurement. Neutron stresses have been referenced to the X-ray stresses as well because a verifiably stress free neutron measurement is not available yet. Figure 5 shows some correlation in the methods, however more verification is necessary.

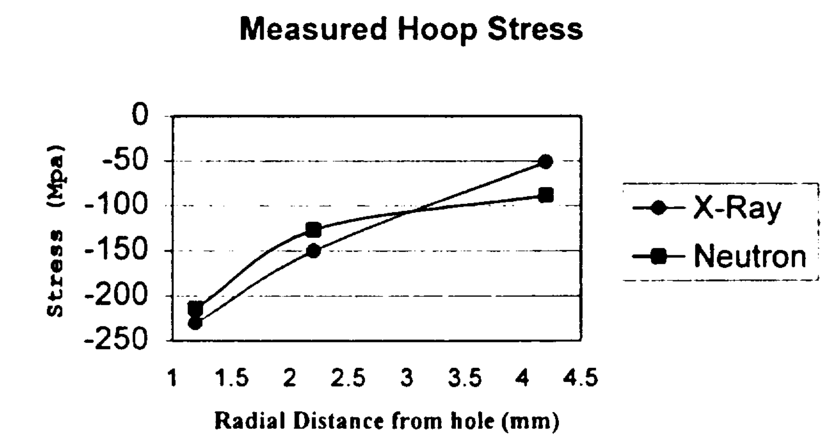

Figure 4: X-ray and Neutron Technique Comparison

Mechanical Testing

The Mechanical Properties Research Laboratory at Georgia Tech provides all the equipment necessary for mechanical testing of the specimens. We are in the process of determining mechanical testing setup for optimum results. Crack growth monitoring is a concern. It was initially proposed to monitor the specimen for crack initiation with an electric potential drop system. A specimen was fitted for the electrodes and tested to failure with the electric potential drop system in place. Unfortunately difficulties in achieving the sensitivity required for initiation detection prevented this system from working properly. Optical crack detection is being used in place of an automatic system. Preliminary mechanical testing of two expendable 2024 specimens under the proposed load levels revealed apparent local yielding around the hole area. This yielding is undesirable because it will interfere with the cold working induced residual stress field of the hole to some extent. Proposed load levels were based on loading situations encountered in aircraft design. Airframe designs typically involve dominantly tensile loading situations. It was found that fatiguing the specimens only in the tensile regime invariably resulted in yielding around the holes for reasonable cycling times. To avoid the problem of hole yielding we will be experimenting with tensile-compressive loading of the specimens. Theoretically, a fully reversed loading test (R=-1) will result in favorable results with regard to cycling time and absence of yielding.

Future Work

Specimens

In order to help resolve the questions that arose in examining the provided specimens it was decided that a set of specimens prepared under very tight tolerances should be created and examined. Dr. Newman of NASA-LaRC has kindly provided the raw material for this. FTI and Oak Ridge National Laboratory have agreed to create the high precision specimens at no additional cost to the program.

The remaining portion of this material will be used for microstructural studies aimed at enhancing diffraction measurement results and for uniaxial mechanical testing. Additionally a study of the stress relaxation of the material at different temperatures may be conducted, as it would be valuable to this research. With some analysis, higher temperature aging results could possibly be used to approximate long-term low temperature aging stress relaxation.

Residual Stress

Future neutron work will develop a complete strain tensor for the specimens in the preliminary condition. Later measurements will be made to assess the state of stress relaxation after thermal processing and bolt bearing treatment of the specimens.

Future X-ray work will be performed at ORNL and will serve the purpose of a check against neutron measurements. The TEC X-ray results will be verified again when X-ray residual stress capabilities are developed at ORNL. X-rays may prove more capable to work on the 2024 material, as grain size problems can be dealt with to some degree through beam manipulations that cannot be accomplished at the neutron diffraction facility.

Previous work worthy of comparison will be considered when measurements on the precision specimens become available. Neutron work on an otherwise nearly identical specimen of 7075 aluminum has been presented by D.Q. Wang, and L. Edwards and will be valuable [4]. David Wang is currently working at ORNL and has already proven to be an asset to the project. X-ray work of interest has also been presented in a paper by M. Priest, C.G. Poussard, M.J. Pavier, and D.J. Smith. The paper details X-ray measurements around a cold worked hole in 2024-T351 plate [5].

Mechanical Properties

We would like to approximate as nearly as possible in our study the dominant tensile loading which occurs in airframes. Loading the specimens only in the tensile regime will not be possible due to considerations of cycling time and yielding. A compromised solution can be attained by determining the largest possible tensile stress range that will give suitable test results. This will be achieved through fatigue tests on the plate material sent to us by Dr. Newman. Testing of the specimens will commence once this fine-tuning of the test parameters has been completed.

Acknowledgements

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References

[1] W.S. Johnson, J.W. Morrow, C.D. Little, "Damage Tolerance Crack Growth Characterization of 7475 Aluminum Material." General Dynamics Research Report, Brochure No. 76006685, Report No. ERR-FW-1753, 1976.

[2] Y.C. Hsu and R.G. Foreman, "Elastic-plastic analysis of an infinite sheet having a circular hole under pressure." J. Applied Mech. 42, 347-352, 1975.

[3] D.L. Rich and L.F. Impellizzeri, "Fatigue analysis of cold worked and Interference fit fastener holes." In: Cyclic Stress-Strain and Plastic Deformation Aspects of Fatigue Crack Growth, ASTM STP 637. pp. 153-175, 1977.

[4] D.Q. Wang and L. Edwards, "Neutron Diffraction Determination of the Complete 3D Residual Stress Distribution Surrounding a Cold Expanded Hole." In: Fourth European Conference on Residual Stresses, V. 2 pp. 619-626, 1994.

[5] M. Priest, C. G. Poussard, M.J. Pavier, D.J. Smith, "An Assessment of Measured and Predicted Residual Stresses Around Cold Worked Holes in AL 2024" In: J Strain Anal Eng Des v 30 n 4 MEP Edmunds Engl p 291-304, 1995.